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जर्मेनियम गामा की परीक्षण कार्यविधियां – रे संसूचक

Indian Standard

TEST PROCEDURES FOR GERMANIUM GAMMA-RAY DETECTORS

UDC 539·166·2·074 : 669·783

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NATIONAL FOREWORD

This Indian Standard which is identical with IEC 973 : 1989 'Test procedures for Germanium Gamma-ray detectors', issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of Nuclear Instrumentation Sectional Committee (LTD 26) and approval of the Electronics and Telecommunication Division Council. In the adopted standard certain terminology and conventions are however not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.

b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

In this Indian Standard, the following International Standards are referred to. Read in their respective place the following:

International Standard	*Indian Standard*	*Degree of Equivalence*
IEC 333 : 1983 Test procedure for semiconductor charged-particle detectors	IS 11425 : 1985 IEC 333 : 1983 Test procedures for semiconductor charged particle detectors	Identical
IEC 759 : 1983 Standard test procedures for semiconductor X-ray energy spectrometers	IS 12737 : 1988 IEC 759 : 1983 Standard test procedures for semiconductor X-ray energy spectrometers	Identical

Only the English language text in the international standard has been retained while adopting it in this Indian Standard.

Indian Standard

TEST PROCEDURES FOR GERMANIUM GAMMA-RAY DETECTORS

1. Scope

This standard applies to germanium radiation detectors which are primarily used for detection and high-resolution spectroscopy of gamma radiation. These devices are also used for X-ray spectroscopy and occasionally for charged particle spectroscopy.

This standard describes the measurement of detector system performance characteristics which are important to the detector user. The measurement techniques described have been selected to be readily available to manufacturers and users of germanium detectors.

2. Object

The object of this standard is to establish standard test procedures for germanium gamma-ray detectors so that measurements have the same meaning to all manufacturers and users.

Not all tests described in this standard are mandatory, but tests which are used to specify performance shall be performed in accordance with the procedures described herein.

3. Symbols and definitions

3.1 *Symbols*

A = peak area
A_b = peak background area
A_t = total peak area
a, b = constants characterizing noise
B = bandwidth
C = electrical capacitance
C_c = calibrated capacitor used to couple pulse generator to circuit under test

C_{eff} = effective input capacitance of a preamplifier
C_f = feedback capacitance in the charge-sensitive loop of a preamplifier

C_t = total capacitance at preamplifier input
Δ = full width at half maximum (FWHM) of a spectral peak
ΔE_A = FWHM, expressed in units of energy, due to amplifier noise
ΔE_D = FWHM, expressed in units of energy, due to detector noise
ΔE_E = FWHM, expressed in units of energy, due to electronic noise without the detector noise contribution
ΔE_o = FWHM, expressed in units of energy, due to all factors other than electronic noise

ΔE_S = FWHM, expressed in units of energy, derived in spectral energy resolution measurement

ΔE_T = FWHM, expressed in units of energy, due to the combined effects of detector and amplifier noise

ΔN_A = FWHM, expressed in channels, due to amplifier noise

ΔN_D = FWHM, expressed in channels, due to detector noise

ΔN_E = FWHM, expressed in channels, due to electronic noise without the detector noise contribution

ΔN_O = FWHM, expressed in channels, due to all factors other than electronic noise

ΔN_s = FWHM, expressed in channels, of a spectral peak used for energy resolution determination

ΔN_T = FWHM, expressed in channels, due to the combined effect of detector and amplifier noise

ΔQ_A = FWHM, expressed in units of charge, due to amplifier noise

ΔQ_D = FWHM, expressed in units of charge, due to detector noise

ΔQ_E = FWHM, expressed in units of charge, due to the electronic noise without the detector noise contribution

ΔQ_T = FWHM, expressed in units of charge, due to the combined effects of detector and amplifier noise

Δt = duration of a pulse, the time interval between the half amplitude points of a pulse

ΔV_e = voltage difference signal related to the nonlinearity of an amplifier

E, E_i = energy of a particle or radiation (or energy of a specific value, E_i, where i is an integer, 1, 2, ...)

ε = average energy required to form one hole-electron pair in a semiconductor detector

e = charge of the electron

e_{ni} = equivalent root-mean-square noise voltage referred to the preamplifier input

e_{no} = root–mean-square noise voltage

e_{qi} = root-mean-square noise in units of charge at the amplifier input

I = electric current

I_d = detector leakage current

N_c = number of counts in channel c of a multichannel pulse-height analyzer spectrum where channel c lies within a specified energy range within the Compton continuum

N_X = number of counts in channel X of a multichannel pulse-height analyzer spectrum

Q = electric charge

R = electrical resistance

T = absolute temperature

t_o = observed detector rise time due to the combined effects of the charge collection time and electronic rise time (10% to 90%)

$t_{0.5}$ = pulse width at half maximum

t_c = charge collection time in a detector (10% to 90%)

t_d = pulse decay time (90% to 10% of peak height)

t_r = pulse rise time (10% to 90% of its peak value)

τ = time constant

τ_d = time constant for the decay of a pulse

V = electric voltage

V_a = amplitude of pulse amplifier output voltage
V_b = detector bias voltage
V_g, V_{gi} = output voltage of precision pulse generator, and that voltage corresponding to energy E_i
V_p, V_{pi} = amplitude of the voltage step impressed on a calibrated capacitor C_c by the pulse generator, and that voltage amplitude corresponding to energy E_i
X, X_i = channel number, and that channel number corresponding to energy E_i
X = interpolated channel number corresponding to the maximum of a monoenergetic spectral peak
Z = characteristic impedance

3.2 *Definitions (in alphabetical order)*

Avalanche breakdown (of a semiconductor device) — (Claquage par avalanche)

A breakdown that is caused by the cumulative multiplication of charge carriers through field-induced impact ionization.

Ballistic deficit — (Déficit balistique)

The loss in signal amplitude that occurs when the charge collection time in a detector is a significant fraction of the amplifier's differentiating time constant.

Band gap (in a semiconductor) — (Largeur de bande interdite)

The difference in energy between the energy level of the bottom of the conduction band and the energy level of the top of the valence band.

Baseline (at pulse peak) — (Ligne de base)

The instantaneous value that the voltage would have had at the time of the pulse peak in the absence of that pulse.

Bias (of a semiconductor radiation detector) — (Tension de polarisation)

The voltage applied to a detector to produce the electric field to sweep out the signal charge.

Biased amplifier — (Amplificateur à seuil)

An amplifier giving essentially zero output for all inputs below a threshold and having constant incremental gain for all inputs above the threshold up to a specified maximum amplitude.

Bias resistor (of a semiconductor radiation detector) — (Résistance de polarisation)

The resistor through which bias voltage is applied to a detector.

Breakdown (of a semiconductor diode) — (Claquage).

A phenomenon occurring in a reverse-biased semiconductor diode, the initiation of which is observed as a transition from a region of high dynamic resistance to a region of substantially lower dynamic resistance for increasing magnitude of reverse current.

Breakdown region (of a semiconductor diode characteristic) — (Zone de claquage)

That entire region of the voltage-current characteristic beyond the initiation of breakdown for increasing magnitude of reverse current.

Breakdown voltage (of a semiconductor diode) — (Tension de claquage)

The voltage measured at a specified current in the breakdown region.

Capacitance (of a semiconductor radiation detector) — (Capacité)

The small-signal capacitance measured between terminals of the detector under specified conditions of bias and frequency.

Channel, surface (of a semiconductor radiation detector) — (Canal, surface)

A thin region at a semiconductor surface, of p- or n-type conductivity created by the action of an electric field, for example, that due to charges trapped in surface layers.

Channelling, lattice (in a semiconductor radiation detector) — (Canalisation, réseau)

A phenomenon that results in a crystallographic directional dependence of the rate of energy loss of ionizing particles.

Charge carrier (of a semiconductor) — (Porteur de charge)

A mobile conduction electron or mobile hole.

Charge collection time (of a semiconductor radiation detector) — (Temps de collection des charges)

The time interval, after the passage of an ionizing particle, for the integrated current flowing between the terminals of the detector to increase from 10% to 90% of its final value.

Charge-sensitive preamplifier — (Préamplificateur de tension)

An amplifier, preceding the main amplifier, in which the output signal amplitude is proportional to the charge injected at the input. See voltage-sensitive preamplifier.

Coaxial detector — (Détecteur coaxial)

A semiconductor radiation detector in which all or part of the two electrical contacts are substantially coaxial. Typically one end of each contact configuration is closed (closed-end coaxial detector), but both ends may be open (open-end coaxial detector).

Cooled-input FET preamplifier — (Préamplificateur à TEC d'entrée refroidi)

A preamplifier in which the input FET (Field Effect Transistor) is cooled to reduce noise.

Constant-fraction discriminator — (Discriminateur à fraction constante)

A pulse discriminator which gives an output when the amplitude of the input signal, delayed, matches a selected fraction of the undelayed signal. The instant of matching is invariant with input-signal amplitude, and if the delay is less than the fastest charge collection time, the timing spread in the instant of matching will be less than that in the charge collection time. The timing jitter is minimized by appropriate choices of fraction and delay (see Figure 9.1.2).

Conventional-electrode coaxial detector (jargon) — (Détecteur coaxial conventionnel [jargon])

A coaxial detector in which the outer contact is an n-type layer.

Crest factor (of an r.m.s. voltmeter) — (Facteur de crête)

The ratio of the peak voltage value to the full-scale value of the range being used for measurement that an average reading or root-mean-square voltmeter will accept without overloading.

Crossover time — (Instant de passage)

The instant at which the waveform of a bipolar pulse passes through a designated level (usually zero).

Crossover walk (of a pulse) — (Imprécision sur l'instant de passage)

The deviation of the crossover time as a function of some variable, such as pulse amplitude.

CR-RC shaping — (Mise en forme CR-RC)

The pulse shaping present in an amplifier that has a simple high-pass filter consisting of a capacitor and a resistor together with a simple low-pass filter, separated by impedance isolation. (Pulse shaping in such an amplifier cuts off at 6 dB per octave at both ends of the band.)

Dead layer (of a semiconductor radiation detector) — (Zone morte)

A layer of a semiconductor detector in which no significant part of the energy lost by particles can contribute to the resulting signal.

Note. — The semiconductor detector may have an entrance and an exit dead layer.

Decay time constant — (Constante de temps de décroissance)

The time for a true single-exponential waveform to decay to a value of $1/e$ of the original step height.

Depletion region (in a semiconductor) — (Région de déplétion)

A region in which the mobile charge-carrier charge density is insufficient to neutralize the net fixed charge density of donors and acceptors.

In a diode-type semiconductor radiation detector the depletion region is the sensitive region of the device.

Depletion voltage (of a semiconductor radiation detector) — (Tension de déplétion)

The voltage at which a junction detector becomes fully depleted.

Differential dE/dX detector — (Détecteur différentiel dE/dX)

A transmission detector whose thickness is small compared to the range of the incident particle and whose entrance and exit dead layers are small compared to the thickness of the detector.

Differentiated (pulse) (pulse amplifier jargon) — (Différencié(e) [impulsion])

A pulse is "differentiated" when it is passed through a high-pass network, such as a CR filter.

Diffused-junction detector — (Détecteur à jonction diffusée)

A semiconductor detector in which the p–n or n–p junction is produced by diffusion of acceptor or donor impurities.

Diffusion depth (of a semiconductor radiation detector) — (Profondeur de diffusion)

(See junction depth.)

Encapsulation (of a semiconductor radiation detector) — (Encapsulation)

The packaging of a detector for protective and/or mounting purposes.

Energy resolution (FWHM) of a semiconductor radiation detector — (Résolution en énergie (LTMH) d'un détecteur semiconducteur)

The detector's contribution (including detector leakage current noise), expressed in units of energy, to the FWHM of a pulse-height distribution corresponding to an energy spectrum.

Energy resolution (FWHM) of a semiconductor radiation detector/preamplifier combination — (Résolution en énergie [LTMH] d'un ensemble détecteur semiconducteur-préamplificateur)

The FWHM, measured at a specific energy and expressed in energy units, of a spectral peak within a pulse-height distribution corresponding to an energy spectrum.

Equivalent noise referred to input (of a linear amplifier) — (Bruit équivalent à l'entrée)

The value of noise at the input that would produce the same value of noise at the output as does the actual noise source.

Equivalent noise resistance referred to input (of a linear amplifier) — (Résistance équivalente de bruit ramené à l'entrée d'un amplificateur linéaire)

That value of resistor which when applied to the input of a hypothetical noiseless amplifier with the same gain and bandwidth would produce the same output noise.

Full width at half maximum — (Largeur totale à mi-hauteur)

The full width of a distribution measured at half the maximum ordinate. For a normal distribution, it is equal to $2(2 \ln 2)^{1/2}$ times the standard deviation σ.

FWHM (See full width at half maximum) — (LTMH)

FW 0,1 M — (LT 0,1 M)

Same as FWHM except that measurement is made at one-tenth the maximum ordinate rather than at one-half.

FW 0,02 M — (LT 0,02 M)

Same as FWHM except that the width measurement is made at one-fiftieth the maximum ordinate rather than at one-half.

Gated integrator — (Intégrateur à porte)

A circuit for obtaining a pulse with an amplitude proportional to the integral of a signal pulse over a definite time interval.

High-purity germanium (HPGe) — (Germanium de haute pureté [GeHP])

Germanium whose net concentration of electrically active impurities which are stable at room temperature is such that conventional-sized radiation detectors made from it achieve full depletion at reasonable bias voltages. (The net concentration of electrically active impurities is typically less than 3×10^{10} cm^{-3}.)

Ion-implanted contact — (Contact implanté)

A detector contact consisting of a junction produced by ion implantation.

Ion implantation — (Implantation ionique)

A process in which a beam of energetic ions incident upon a solid results in the imbedding of those ions into the material.

Inactive region (of a semiconductor radiation detector) — (Région inactive)

A region of a detector in which charge created by ionizing radiation does not contribute significantly to the signal charge.

Integrated (pulse) (pulse amplifier jargon) — (Intégré[e] [impulsion] [jargon])

A pulse is "integrated" when it is passed through a low-pass network, such as a single RC network or a cascaded RC network.

Integrating preamplifier — (Préamplificateur intégrateur)

A pulse preamplifier in which individual pulses are intentionally integrated by passive or active circuits.

Intrinsic semiconductor — (Semiconducteur intrinsèque)

A semiconductor containing an equal number of free holes and electrons throughout its volume. (The term "intrinsic germanium" is often used incorrectly for high-purity germanium.)

Junction (of a semiconductor radiation detector) — (Jonction)

A region of transition between semiconductor regions of different electrical properties (e.g. $n\text{–}n^+$, p–n, $p\text{–}p^+$ semiconductors), or between a metal and a semiconductor.

Junction depth (of a p–n semiconductor radiation detector) — (Profondeur de jonction)

The distance below the crystal surface at which the conductivity type changes.

Leakage current (of a semiconductor radiation detector) — (Courant de fuite)

The total detector current flowing at the operating bias in the absence of radiation.

Lithium-drifted detector — (Détecteur compensé au lithium)

A detector made by the lithium compensation process.

Lithium drifting — (Compensation au lithium)

A technique for compensating p-type material by causing lithium ions to move through a crystal under an applied electric field in such a way as to compensate the charge of the bound acceptor impurities.

Load impedance (of a semiconductor radiation detector) — (Impédance de charge)

The impedance shunting the detector, and across which the detector output voltage signal is developed.

Load resistance (of a semiconductor radiation detector) — (Résistance de charge)

The resistive component of the load impedance.

Marinelli beaker — (Récipient de Marinelli)

See reentrant beaker.

Noise linewidth — (Résolution électrique)

The contribution of noise to the width of a spectral peak.

Noninjecting contact (of a semiconductor radiation detector) — (Contact non injectant)

A purely resistive contact, i.e. one that has a linear voltage-current characteristic throughout its entire operating range.

Peaking time (t_p) *(of an amplifier output pulse)* — (Instant de crête [t_p] [d'une impulsion de sortie d'amplificateur])

The time between the 1% amplitude point on the leading edge and the 100% amplitude point of a pulse (provided that the pulse does not have a flat top). For flap-topped pulses the peaking time is defined as the time between the 1% amplitude point and the mid-point of the flat top.

p-i-n detector — (Détecteur p.i.n)

A detector consisting of an intrinsic or nearly intrinsic region between a p and n region.

Pulse decay time (t_d) — (Temps de descente d'une impulsion [t_d])

The interval between the instants at which the instantaneous value last reaches specified upper and lower limits, namely, 90% and 10% of the peak value unless otherwise stated.

(In the case of a step function applied to an amplifier that has simple CR-RC shaping, the decay time is given by t_d = 3,36 CR.)

Pulse optical feedback preamplifier — (Préamplificateur à contre-réaction opto-électronique pulsée)

A charge-sensitive preamplifier in which the charge which accumulates on the feedback capacitor is periodically reset by a pulse of light incident on a suitable photosensitive element (e.g. the n–p junction of the gate of the input FET).

Pulse rise time (t_r) — (Temps de montée d'une impulsion [t_r])

The interval between the instants at which the instantaneous value first reaches specified lower and upper limits, namely, 10% and 90% of the peak pulse value unless otherwise specified.

(In the case of a step function applied to an RC low-pass filter, the rise time is given by t_r = 2,2 RC. In the case of a step function applied to an amplifier that has simple

CR–RC shaping, i.e., one high-pass and one low-pass RC filter of equal time constants, the rise time is given by $t_r = 0,57$ RC.)

Pulse width at half max. $T_{0,5}$ *(of an amplifier output pulse)* — (Durée l'impulsion à mi-hauteur, $T_{0,5}$)

The time interval between the 50% of maximum amplitude points of a pulse.

Punch-through voltage (of a semiconductor radiation detector) — (Tension de désertion totale)

(See depletion voltage).

Quasi-Gaussian shaping — (Mise en forme quasi gaussienne)

Pulse shaping consisting of one differentiation followed by four or more integrations which result in a pulse shape that is approximated by a Gaussian curve. For n integrations the shaping network is sometimes denoted as $CR–(RC)^n$.

RBSS — (SNRE)

Acronym for reentrant beaker standard source.

Reentrant beaker — (Récipient enveloppant)

A reentrant (inverted well) beaker which will hold a radioactive sample and fit over a detector endcap such that the detector is essentially surrounded by the sample. (Also referred to as a Marinelli beaker.)

Resistive feedback preamplifier — (Préamplificateur à contre-réaction résistive)

A charge-sensitive preamplifier in which charge which accumulates on the feedback capacitor is continually discharged through a resistor in parallel with the capacitor.

Reverse-electrode coaxial detector — (Détecteur coaxial inversé)

A coaxial detector in which the outer contact is a p-type layer.

Schottky barrier contact — (Contact à barrière de Schottky)

A metal semiconductor contact structure whose rectification properties are heavily influenced by the difference in both material work functions. These contacts may utilize an interfacial metal/semiconductor compound.

Schottky barrier radiation detector — (Détecteur à barrière de Schottky)

A semiconductor radiation detector whose blocking contact is a Schottky barrier contact.

Semiconductor, compensated — (Semiconducteur compensé)

A semiconductor in which one type of impurity or imperfection (e.g. donor) partially cancels the electric effects of the other type of impurity or imperfection (e.g. acceptor).

Semiconductor radiation detector — (Détecteur semiconducteur)

A semiconductor device that utilizes the production and motion of excess free charge carriers in the semiconductor for the detection and measurement of particles or photons of incident radiation.

Space-charge generation (in a semiconductor radiation detector) — (Génération de charge d'espace)

The thermal generation of free charge carriers in the space-charge region.

Spectral line — (Pic spectral)

A sharply peaked portion of the spectrum that represents a specific feature of the incident radiation, usually the full energy of a monoenergetic radiation.

Spectrum (radiation) — (Spectre)

A distribution of the intensity of radiation as a function of energy or its equivalent electric analog (such as charge or voltage) at the output of a radiation detector.

Straggling, energy — (Fluctuation de perte d'énergie)

The random fluctuations in energy loss whereby those particles having the same initial energy lose different amounts of energy when traversing a given thickness of matter. (This process leads to the broadening of spectral lines.)

Surface barrier contact — (Contact à barrière de surface)

A metal-insulator-semiconductor (MIS) contact structure whose rectification properties are dominated or heavily influenced by charge trapped at the interfaces and in the insulator.

Surface barrier radiation detector — (Détecteur à barrière de surface)

A radiation detector for which the principal rectifying junction is a surface barrier contact.

Time-invariant filtering — (Filtrage invariant dans le temps)

Pulse shaping in which the filter response does not change with respect to time. (CR–[RC]^n shaping is an example of time-invariant filtering.)

Time-variant filtering — (Filtrage variant dans le temps)

Pulse shaping in which the filter response is not constant with respect to time. This is often achieved by a gated integrator following a time-invariant filter. The integrator is gated on for the duration of each pulse.

Totally depleted detector — (Détecteur totalement déserté)

A detector in which the thickness of the depletion region is essentially equal to the thickness of the semiconductor material.

Transistor reset preamplifier — (Préamplificateur à remise à zéro par transistor)

A charge-sensitive preamplifier in which the charge which accumulates on the feedback capacitor is periodically discharged through a suitably located transistor.

Voltage-sensitive preamplifier — (Préamplificateur sensible à la charge)

An amplifier preceding the main amplifier, in which the output-signal amplitude is proportional to the signal voltage appearing across the capacitance that exists at the input of the preamplifier. See charge-sensitive preamplifier.

Well-type coaxial detector — (Détecteur coaxial puits)

A coaxial detector which is mounted and encapsulated in such a way that radioactive samples may be inserted within the inner cylindrical electrode such that the sample is essentially surrounded by active detector material.

4. Introduction

4.1 *The interaction of gamma-rays with matter*

Gamma-rays interact with matter through three principal processes: the photoelectric effect, the Compton effect and pair production. For narrow beam geometry, the attenuation of an incident photon beam can be described by a simple exponential law of the form:

$$N_y = N_o \exp(-\mu y)$$

where N_o represents the number of incident photons, and N_y is the number remaining after traversing absorber thickness y. The total linear attenuation coefficient μ is the sum of three terms representing the three previously mentioned processes.

The photoelectric effect takes place when an incident photon transfers its entire energy to a bound electron in an atom, resulting in the ejection of the electron. The ejected electron has kinetic energy equal to the photon energy less the electron binding energy. The cross section for the photoelectric effect increases rapidly with the atomic number of the absorber ($\sim Z^4$ per atom) and decreases rapidly with increasing energy ($\sim E^{-3}$).

The Compton effect may be considered as an elastic collision of a photon with an atomic electron. The electron is ejected from the atom, and the photon is scattered with reduced energy. The scattered photon may then interact through an additional process. The cross section for the Compton effect decreases with increasing energy, but much less rapidly than for the photoelectric effect.

Pair production takes place when the energy of a photon is converted into an electron and a positron in the presence of a nearby nucleus or electron. For pair production to take place, the photon shall have a minimum energy of 1,02 MeV, the sum of the rest mass energies of the electron and the positron. Above this energy, the cross section for pair production increases with increasing photon energy. Because of screening effects, its rate of increase is gradually reduced as photon energy increases.

The linear attenuation coefficients for silicon and germanium are shown in Figure 4.1.1. In all of these absorption processes the energy of incident photons is transferred to one or more electrons. These electrons rapidly lose their energy in the absorber material largely through Coulomb interactions resulting in the removal of electrons from atoms along the energetic electron's path. Part of energy from these processes also results in phonon production.

Thus, the principal result of the interaction of gamma rays with matter is ionization. In a semiconductor material this is manifested as the creation of a large number of electron-hole pairs, the quantity being directly proportional to the absorbed energy of the incident photon. The average energy necessary to create an electron-hole pair is 3,0 eV in germanium at 77 K and 3,6 eV in silicon at room temperature.

4.2 *The germanium gamma-ray detector*

The germanium detector element is a single crystal of germanium that has been made into a diode capable of withstanding high reverse bias voltage at cryogenic temperature. With bias voltage applied, the bulk of the detector becomes depleted of free charge carriers. Under these conditions, electrons and holes generated by the absorption of gamma rays are swept to opposite contacts by the electric fields in the depletion region. The resulting induced charge is integrated to produce an output pulse whose magnitude is proportional to the absorbed photon energy.

Germanium detectors are usually mounted within a cryostat to permit cooling the detector and maintaining it at cryogenic temperature for the purpose of reducing leakage current and thermal noise. The cryostat also provides protection and an appropriate environment for the detector. A preamplifier and high voltage filter are usually combined in an intergrated unit with the cryostat and detector. Thus it is usually not practical to measure performance of the detector element as an isolated unit. Most stated measurements apply to the integrated unit.

4.3 *Germanium detector types*

Germanium detector types are differentiated by material, geometry, and mode of use. Materials used are typically high-purity p-type germanium, and high-purity n-type germanium. Previously lithium-compensated germanium was widely used.

Commonly used geometries are planar and coaxial. Hybrids of these geometries are often used. These terms apply to the configuration of electrical contacts. Planar detectors (Figure 4.3.1) are usually disc shaped with contacts which are parallel planes. Coaxial detectors (Figure 4.3.2) have contacts which are in the form of coaxial cylinders which may be closed on one end.

The coaxial geometry makes possible detectors with large volumes that have relatively high efficiency for detecting higher-energy gamma-rays for which absorption cross sections are small; planar geometry is useful for constructing small-diameter, low capacitance devices which make possible low preamplifier noise, an essential factor for obtaining high resolution especially at low photon energies.

Planar detectors can also have large front surface areas at the expense of higher capacitance. This can be an efficient structure for detecting low-energy photons. A thin outer contact facilitates the use of this type of detector for low energy X-rays.

Hybrid detector geometries are frequently employed and can be suited to the particular application.

The conventional electrode (p-type) coaxial detector is made with p-type high-purity germanium (Figure 4.3.2a) with an n^+ outer contact (frequently lithium diffusion). The inner contact can be a metallization or a p-type ion implantation. Positive bias voltage is applied to the outer contact to achieve diode depletion.

The reverse-electrode coaxial detector (n-type) is made with a p^+ outer contact. This outer contact may be made by metallization or ion implantation/(Figure 4.3.2b). The inner contact is typically lithium diffusion, but it can be any non-injecting contact. Negative bias voltage is applied to the outer contact to achieve diode depletion. Thin outer contacts make it possible to use this detector for X-ray spectroscopy as well as higher-energy gamma-ray spectroscopy. The thin outer contact makes it particularly appropriate for use with anti-Compton shielding. Reverse-electrode coaxial detectors are more resistant to neutron damage than are conventional electrode coaxial detectors.

The lithium compensated germanium, Ge(Li), coaxial detector is made from p-type germanium through which lithium ions have been drifted in an electric field to provide acceptor compensation (Figure 4.3.2c). The resulting material behaves approximately as intrinsic germanium if the compensation is precise.

Because compensation is unstable at room temperature, Ge(Li) detectors shall be kept at liquid nitrogen temperature at all times.

The outer contact is an n-type lithium diffusion. The inner contact is normally the undrifted core of p-type material. Coaxial detectors may have the electrodes in an open-ended or a closed-ended configuration.

Well-type coaxial detectors are mounted and encapsulated in such a way that radioactive samples may be inserted within the inner electrode; the sample is essentially surrounded by active detector volume (Figure 4.3.2d).

Typically a conventional electrode detector is used. The hole for the inner electrode faces the end window. The endcap contains a well which protrudes into the inner electrode.

General requirements

The following requirements apply for all tests and measurements described in this standard:

a) Maximum detector bias voltage, device ambient temperature and environment, and other operational limits specified by the detector manufacturer should not be exceeded since permanent changes of the detector characteristics may result.

b) The detector bias supply, amplifier, multichannel analyzer, and other test equipment shall not significantly influence the detector parameter measurements because of instability, nonlinearity or other performance defects.

c) All measurements shall be made and reported in accordance with good scientific practice. Changes in test system components or changes in system parameters (e.g. amplifier gain) shall not be made without complete system recalibration. Results which contain the effects of changing more than one parameter shall explicitly show the effects of each parameter on the measurement.

d) The values of the parameters measured should be reproducible within the stated precision of the measurement after the performance of any one or all of the tests performed.

6. Energy spectroscopy measurements

Tests for evaluating the characteristics of germanium detectors involve the determination of a number of parameters of a peak in a spectral pulse-height distribution. The derivation and use of these peak parameters are discussed in this clause. The methods described have been chosen for their simplicity and ease of computation, although it is recognized that under certain circumstances, such as in the presence of seriously distorted spectral peaks, computer fitting may yield more precise results. For the analyses described below, a spectral peak shall be at least six channels wide at half-maximum and the total number of counts within the FWHM shall be at least 50 000. Energy resolution, peak shape, and peak-to-Compton ratio are sensitive to the detector-source geometry. The source shall be located on-axis, 25 cm from the center of the front of the detector endcap, unless otherwise specified.

6.1 *Useful radionuclide sources*

The radiation sources listed below are recommended for specifying measurements of energy resolution for the detector and spectrometry system or both:

Radiation source	Half-life	Energy
^{55}Fe	2,7 y (year)	5,9 keV*
^{241}Am	433 y	59,5 keV*, 26,36 keV, X-rays
^{109}Cd	453 d (days)	22,1 keV* (X-ray doublet), 88,0 keV*
^{57}Co	270 d	122,1 keV* and 136,5 keV
^{137}Cs	30 y	661,6 keV*
^{22}Na	2,60 y	1 274,5 keV*
^{60}Co	5,24 y	1 173,2 keV* and 1 332,5 keV+*
^{208}Tl	1,91 y	2 614,5 keV* (^{228}Th source)

+ This line is preferred for coaxial detector specifications.

* Gamma- and X-rays recommended for energy resolution measurements.

Widely used multi-line sources are 77 d ^{56}Co with gamma-rays ranging in energy from 847 keV to 3 600 keV, and 13 y ^{152}Eu with gamma rays ranging in energy from 122 keV to 1 769 keV. In energy resolution measurements, it is assumed that the system is calibrated in terms of eV, or keV per channel.

This can be achieved by using calibration lines which should be sufficiently close in energy to the peak under study to reduce problems arising from system nonlinearities. For example, in the case of ^{60}Co, the 1 173,2 keV and 1 332,5 keV lines are suitable for this purpose, but in the case of the monoenergetic gamma-emitter ^{137}Cs, it is possible to use a supplementary source such as ^{207}Bi (569,7 keV) or ^{54}Mn (835 keV) to provide an additional line.

6.2 *Method*

Connect the detector to an integrating preamplifier, main amplifier, and multichannel pulse-height analyzer as shown in Figure 6.2.1.

Note. — The detector and preamplifier may be supplied as an integral unit; coupling may be a.c or d.c. Amplifier pulse shaping suitable for optimum performance of the detector may be used. The type of amplifier pulse shaping used and the full width at half maximum of the pulse shall be given with each stated resolution measurement or specification. A pulse generator (specified by IEC 333), connected to the system as shown in Figure 6.2.1, can be run simultaneously with the gamma-ray counting, provided it is demonstrated that the pulser does not distort other peaks (e.g. by baseline undershoot) or cause significant errors in dead-time correction in the case of an efficiency measurement.

6.3 *Peak area and spectral background*

Pulse-height spectral data should be plotted as the log of the number of counts N_X in channel X versus channel number X. On this semilog plot, straight lines representing an approximation to the background distribution under the peak should be fitted to sections of the pulse-height distribution on either side of the peak, for example, the lines *a–d* and *e–h* shown in Figure 6.3.1. The mean value of groups of 10 data points may be used to facilitate fitting the background lines above and below the peak. Draw a smooth curve through the peak data points, extending the curve on each side at the base of the peak to intersect the background lines, for example, *E–F* and *G–H* in Figure 6.3.1. The background under the peak is considered to be the area below the straight line bounded by the points of intersection with the peak curve lines, for example, *A–D* and *E–H* in Figure 6.3.1.

The total peak area A_t is obtained by summing the counts per channel in the peak distribution over the curve bounded by the points of intersection with the background line:

$$A_t = \sum_{X=E}^{H} N_X \qquad (1)$$

Similarly, the area of the background A_b is found by summing the counts per channel B_x for the background:

$$A_b = \sum_{X=E}^{H} B_X \qquad (2)$$

The area of the peak A is then given by:

$$A = A_t - A_b \qquad (3)$$

6.4 *Peak center*

Calculate, point by point, the number of counts per channel less background $N_X - B_X$ as a function of channel number X. Determine the interpolated fractional channel number $\hat{X}$ corresponding to the maximum of the monoenergetic spectral peak (see Figure 6.4.1). A convenient technique is the weighted average method for values of N in the symmetrical portion of the peak, for example, above the half-maximum height:

$$\hat{X} = \Sigma X\,(N_X - B_X)\ /\ \Sigma(N_X - B_X) \tag{4}$$

6.5 *FWHM, FW 0,1 M and FW 0,02 M of a peak*

On a linear plot of $N_X - B_X$ versus X, determine the ½, ⅒ and ¹⁄₅₀ height of the peak. Determine the FWHM, FW 0,1 M, FW 0,02 M of the peak in channels ΔN_s (interpolated). Ratios of these values (FW 0,1 M/FWHM and FW 0,02 M/FWHM) are often given as indicators of peak shape quality.

6.6 *Peak-to-Compton ratio*

Determine the average height $\overline{N}_c$ of the portion of the Compton continuum in the average region defined by the relatively flat interval from 358 keV to 382 keV for the ^{137}Cs 661,6 keV gamma-ray or 1 040 keV to 1 096 keV for the ^{60}Co 1 332,5 keV gamma-ray. These selected regions avoid the Compton edge. The peak-to-Compton ratio is defined as the ratio of the maximum number of counts in the peak, $\hat{N}_X$ at channel number $\hat{X}$, to $\overline{N}_c$ (see Figure 6.6.1). Note that in general $\hat{X}$ and $\hat{N}_X$ are interpolated values. The source used shall be stated.

The peak-to-Compton ratio is a detector performance index which depends on detector geometry, mount and cryostat construction, detector efficiency and detector resolution. This ratio is inversely proportional to resolution if other factors remain unchanged. It generally increases with increasing detector efficiency, but the extent of this effect is determined by the specific nature of the accompanying changes in detector geometry.

Other things being equal, the peak-to-Compton ratio is greater for detector geometries which maximize the probability of total absorption of the energy of photons which are initially Compton scattered within the detector. The peak-to-Compton ratio is adversely affected by Compton scattering which occurs in material (including inactive detector germanium) which is near the detector or source. Typically, detectors with larger peak-to-Compton ratios have larger line-to-background ratios and better counting statistics for complex spectra.

6.7 *Spectral energy resolution*

The peak to be measured and a second peak should be located in the spectrum and their centres $\hat{X}_1$ and $\hat{X}_2$ determined for the purpose of energy calibration (see 6.4). If needed, the second peak may be produced by a calibrated precision pulse generator. (See IEC 333, 4.1, for pulser calibration instructions.)

On a linear plot of $N_X - B_X$ determine the FWHM of the peak in channels ΔN_s (interpolated). From the energy and location of the peak being measured, E_1 and $\hat{X}_1$, and of a second peak, E_2 and $\hat{X}_2$, the FWHM in energy units is given as follows:

$$\Delta E_s = \frac{E_1 - E_2}{\hat{X}_1 - \hat{X}_2}\,\Delta N_s \tag{5}$$

The value ΔE_s is the total spectral energy resolution at energy E_1.

The type of amplifier pulse shaping used and the full width at half maximum of the pulse shall be given with each stated resolution measurement or specification. Also, the count rate at which the resolution was measured and the maximum count rate-energy product (CREP) capability of the preamplifier used shall be stated. The maximum CREP corresponds to the maximum rate of energy input at which the preamplifier will still operate within its linear response range. For example, in a resistive feedback preamplifier the maximum CREP is determined by the feedback resistor and the maximum feedback voltage. The count rate-energy product is defined as:

$$\mathrm{CREP} = \sum_{E} E \times r_E \ (\mathrm{keV}\ s^{-1})$$

where r_E is the count rate (c/s^{-1}) at the energy E in keV.

6.8 *Total noise linewidth and detector contributic*

Separately or as part of the same spectrum, obtain a gamma-ray spectrum and a pulser-generated peak. Measure ΔE_s, FWHM for the gamma-ray peak, and ΔE_T, FWHM for the pulser peak. Refer to IEC 333 if more information is needed about using a pulser to measure noise. The value of ΔE_T is the total noise linewidth for the spectroscopy system. The contribution to the spectral linewidth due to all factors other than electrical noise is designated as ΔE_o and is given by:

$$\Delta E_o = (\Delta E_s^2 - \Delta E_T^2)^{1/2} \tag{6}$$

If the data have been acquired at a sufficiently low count rate to eliminate count rate effects, ΔE_o is primarily due to the detector charge generation and collection processes and, is an important characteristic of the detector.

6.9 *Peak asymmetry*

Peak asymmetry, due to a number of factors, including carrier trapping and ballistic deficit, appears as tailing on the low-energy side of the gamma-ray peak. Measurements should be made at count rates sufficiently low for peak asymmetry due to count-rate effects from the amplifier to be negligible. For purposes of comparison and evaluation, the following analysis can be used.

On a semilog plot of $(N_X - B_X)$ versus X, draw a line from the apex of the peak at channel $\hat{X}$ perpendicular to the abscissae. Measure, at the 1/10 height level, the width from the low energy side of the peak envelope to the midline (interval L, see Figure 6.9.1). Measure the corresponding interval H on the high energy side of the midline (see Figure 6.9.1). Quote peak asymmetry as the ratio H/L and state the gamma-ray energy for which it applies. The asymmetry ratio may also be calculated at other specified fractional peak heights.

6.10 *Well-type detector resolution*

Since some detectors may have poor charge collection near the inner contact, resolution measurements for well detectors shall be made with an approximate point source located on axis 1,0 cm from the bottom centre of the end cap well (see Figure 4.3.2d). Detectors with a low electric field strength at the inner contact will perform poorly with the source inside the well. The measurement methods and radioactive nuclides used are otherwise the same as for other germanium detectors. However, radioactive sources shall be encapsulated in such a way as to permit easy insertion into the well.

6.11 *Preferred energies*

It is desirable to achieve some standardization in detector resolution measurements. Thus it is preferred to make resolution measurements at specific energies chosen according to the energy range for which the detector is to be evaluated. The preferred energy lines and radionuclides are listed according to energy range as follows:

Energy range	Preferred energy lines and radionuclides
>1 MeV	1 332,5 keV (^{60}Co)
400 keV–1 MeV	661,6 keV (^{137}Cs)
70 keV–400 keV	122,1 keV (^{57}Co)
<70 keV	5,9 keV (^{55}Fe), 22 keV (^{109}Cd)

See 6.1 for a wider range of radionuclide selections. All lines that are unresolved doublets shall be identified, specified and measured without peak deconvolution.

7. **Counting efficiency**

The gamma-ray counting efficiency for a full energy peak or an escape peak depends upon the active volume of the germanium detector, its shape (geometry), source/detector geometry, and interactions in the material in the immediate vicinity of the detector, such as the detector mount and cryostat parts. The efficiency is defined as that of the complete detector assembly.

Three source/detector geometries are specified in this standard: a point source 25,0 cm from the center of the front of the detector endcap, a reentrant beaker standard source placed over the detector endcap, and a point source on axis 1,0 cm from the bottom of the well of a well-type detector. While representative, these geometries do not correspond to all of the many possible geometries which may be used. However, measurements made under these specified conditions provide a standard basis for testing, comparing and selecting detectors for most applications.

When efficiency is quoted as a specification, the type of efficiency measurement shall be clearly stated.

7.1 *Efficiency for a point source at 25,0 cm*

7.1.1 *Absolute full-energy peak counting efficiency*

With the detector connected to the auxiliary electronic equipment as shown in Figure 6.2.1, obtain a spectrum using a calibrated ^{60}Co source. The source-to-cryostat endcap distance (as measured from the center of the source to the center of the front of the endcap) shall be 25,0 cm. The absolute full-energy peak counting efficiency E_a is stated, for purposes of comparison and specification, as the ratio of the number of counts A in the full-energy peak (see 3.1) to the total number of 1 332,5 keV gamma-ray photons N_s emitted by the source during the live counting time:

$$E_a = A/N_s \qquad (7)$$

Alternatively, the counting time may be determined from the area of a pulser peak run at a constant known rate with the pulser line appearing ~5% above the gamma-ray peak in energy. For applications in which a source will be close to the cryostat endcap, an additional efficiency measurement simulating this condition is useful.

7.1.2 *Relative full-energy peak counting efficiency*

The efficiency E_{rel} of a germanium detector relative to that of a 3 × 3 in (76 mm × 76 mm) NaI(Tl) scintillation crystal at a source-to-detector distance of 25,0 cm (as defined in 7.1.1) may be determined from the following:

$$E_{rel} = A/A_{NaI} \qquad (8)$$

where A is the peak area as obtained in 7.1.1.

The term A_{NaI} is $1{,}2 \cdot 10^{-3}\ N_s$ for the 1 332,5 keV gamma-ray emitted from ^{60}Co at a source-to-detector endcap center distance of 25,0 cm.

7.2 *Well-type coaxial detector gamma-ray efficiency*

A well-type coaxial detector has a reentrant cavity well in the endcap which extends into a central hole within the detector element. In a well-type coaxial detector (Figure 4.3.2d) a radionuclide source inserted in the well is essentially surrounded by active germanium. This typically results in a very high absolute efficiency for gamma-ray detection.

For the relatively high absolute efficiency often achieved with a well-type detector, the fraction of coincident gamma rays which are summed is much greater than for geometries in which the source is located outside the endcap. Thus for two lines with coincident gamma rays, a significant sum peak appears in the spectrum. Each count in this peak represents the simultaneous full-energy detection of two gamma rays corresponding to the two lines.

For one of two coincident lines, the number of photons detected at full energy is equal to the sum of the number of counts in the full energy peak A and the number of counts in the sum peak A_s. For an accurate measurement, the number of gamma rays detected which correspond to one such coincident line shall be represented by the sum $(A+A_s)$.

The effect of true coincidence summing in a well detector is an especially important consideration for specifying detector efficiency. As the absolute detector efficiency goes up, the ratio A_s/A increases as a greater fraction of counts falls in the sum peak. Thus if only the number of counts A in the full-energy peak is used to calculate absolute efficiency, the calculated efficiency will become progressively deficient as the actual efficiency increases. To calculate detector efficiency using one of two coincident lines, the sum $(A+A_s)$ shall be used to represent the number of gamma rays detected at full energy corresponding to that line.

Counting efficiency of a well-type detector* should be measured with an approximate point source of ^{60}Co (less than 2,0 mm maximum dimension) located 1,0 cm above the bottom of the end cap well. The method described in 6.2 should be used to accumulate a spectrum. The counting of accidental coincidences shall be made negligible by controlling count rate and amplifier shaping time, and through the use of pulse-pile-up rejection. The 1 332,5 keV line of ^{60}Co is in coincidence with the 1 173,2 keV line resulting in a sum peak at 2 505,7 keV.

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* One commonly used indicator of well detector efficiency has been the active volume of germanium (in cm^3). Active volume (in cm^3) of germanium is not an acceptable detector specification because the user has no way to verify the active detector volume and because it is not a reliable indicator of counting efficiency.

Peak areas of the 1 332,5 keV and the 2 505,7 keV peaks should be determined by the method of 6.3. The in-well efficiency *(W)* is given by:

$$W = \frac{A + A_s}{N_s} \tag{9}$$

where:

A is the area of the 1 332,5 keV peak

A_s is the area of the 2 505,7 keV sum peak

N_s is the total number of 1 332,5 keV photons emitted by the source during the live counting time

7.3 *Detector gamma-ray efficiency using a standard reentrant beaker[1] geometry*

7.3.1 *General*

An efficiency measurement using a standard reentrant beaker geometry is desirable because of an increasing trend towards large-volume, low-activity samples.

Although many reentrant beaker geometries are in use, this standard measurement specifies a single configuration for the purpose of characterizing detector performance. The use of a fixed source geometry allows systematic comparison of the effect of window thickness, sensitive volume, detector shape, and other detector characteristics. The reentrant beaker geometry specified herein (Figures 7.3.1 and 7.3.2) has been chosen primarily for its near-optimum design in placing the sample material as near the active detector material as feasible. Germanium semiconductor detectors are encapsulated in vacuum cryostats such that internal dimensions are not readily measurable by the user. Therefore, in this clause reference is made to the cryostat external dimensions. For the purposes of this clause the detector is considered to be part of a single spectrometer where coincidence or Compton suppression modes are not used. The spectrometer shall be set up and calibrated as specified in Clause 6.

7.3.2 *Reentrant beaker standard source (RBSS)*

A Reentrant Beaker Standard Source (RBSS) consists of a standard reentrant beaker (see 7.3.3) containing a carrier with radioactive material (see 7.3.4). An RBSS may be a certified RBSS, a calibrated RBSS, a certified-solution RBSS or a calibrated-solution RBSS. The calibration uncertainty of the photon emission rate[2] for the filled beaker shall be not more than 3% (1σ) unless otherwise stated.

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[1] Also known as Marinelli beaker.

[2] The photon emission rate as used in this standard is the number of photons per second resulting from the decay of radionuclides in the source and is thus higher than the detected rate at the surface.

7.3.2.1 *Certified RBSS*

A certified RBSS is an RBSS that has been calibrated as to photon emission rate[1] at specified energies by a laboratory recognized as a country's National Standardizing Laboratory for radioactivity measurements and has been so certified by the calibrating laboratory.

7.3.2.2 *Calibrated RBSS*

A calibrated RBSS is an RBSS that has been calibrated by comparing its photon emission rate to that of a certified RBSS.

7.3.2.3 *Certified-solution RBSS*

A certified-solution RBSS is a standard beaker conforming to 7.3.3 that contains a certified solution (see 7.3.2.5) as its radioactive filling material (see 7.3.4).

7.3.2.4 *Calibrated-solution RBSS*

A calibrated-solution RBSS is a standard beaker conforming to 7.3.3 that contains as its radioactive filling material (see 7.3.4) a solution that has been calibrated by comparing its photon emission rate at specified energies to that of a certified solution (see 7.3.2.5).

7.3.2.5 *Certified solution*

A certified solution is a liquid radioactive filling material (see 7.3.4) that has been calibrated by a laboratory recognized as a country's National Standardizing Laboratory for radioactivity measurements and has been so certified by the calibrating laboratory.

7.3.3 *The beaker*

Reentrant beakers are inverted well beakers. They are available in a variety of sizes for use in large-volume, low-level measurements. The beakers specified herein, Models 450 and 1 000, are shown in Figure 7.3.1. Figure 7.3.2 shows a schematic of a typical sample-detector geometry. The Model 450 beaker is considered to be of 450 cm^3 capacity and the Model 1 000 of 1 000 cm^3 capacity. The actual capacities of the beakers are greater than this but, for the purposes of this standard, the beakers are to be filled to those amounts ±2 cm^3 (see 7.3.4). The beakers specified were selected because of:

1) high counting efficiency for the sample material used;

2) commercial availability at low cost;

3) common usage in many laboratories;

4) physical convenience.

7.3.4 *Radioactive filling material*

The beaker used for calibration of detectors with diameters of 76,5 mm or less shall be the Model 450 and for larger diameter detectors shall be the Model 1 000. The 450 cm^3

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[1] International Commission on Radiation Units and Measurements. *Certification of Standardized Radioactive Sources*. ICRU Report No. 12, September 15, 1968.

beaker shall be filled with 450 $cm^3 \pm 2$ cm^3 of a solid or liquid carrier containing uniformly dispersed radioactive material whereas the 1 000 cm^3 beaker shall be filled with 1 000 $cm^3 \pm 2$ cm^3. The solid carrier is preferable for general use because it constitutes a safe and chemically inert sealed source. Representative radionuclides for use in the RBSS are listed in Table 7.3.1.

The carrier shall have an effective atomic number Z of 4,0 ± 0,7 and a mean density of 1,15 ± 0,02 $g.cm^{-3}$ for solid carriers, or 1,06 ± 0,01 $g.cm^{-3}$ for liquid carriers. The density of the carrier used shall be stated (see 7.3.6) so that attenuation corrections may be made. The source activity should be such as not to exceed the count-rate capability of the detector system. In some systems, significant spectral distortion may occur at count-rates as low as a few thousand per second.

7.3.5 *The measurement*

The absolute full-energy peak efficiency of a RBSS *(M)* of a detector assembly being calibrated shall be determined with the RBSS placed over the end cap as in Figure 7.3.2, counted for a live time count interval t and measured according to 6.3 (see also 7.1.1).

M is defined as:

$$M = A/N_s \tag{10}$$

where:

A is the number of events from the RBSS registered as counts in the full-energy peak representing energy E during the live time count interval t

N_s is the number of gamma-rays of energy E originating in the RBSS during the same live time interval t

When the RBSS efficiencies are specified, the energies used in the determination shall be stated. Convenient and frequently used gamma-ray energies include those listed below. The 1332 keV gamma ray of ^{60}Co has been the most widely used for specifying efficiency and resolution. The preferred line at low energies is the 88 keV gamma ray of ^{109}Cd.

88,0 keV (^{109}Cd)
122,1 keV (^{57}Co)
661,6 keV (^{137}Cs)
1 332,5 keV (^{60}Co)

Mixed sources are available which include the above energies plus additional lines.

If the user wishes to extend the use of these techniques to establish a detailed calibration curve for specific applications of the detector, additional energy peaks will generally be required (see Table 7.3.1). Figure 7.3.3 shows typical results for a calibrated RBSS used with two Ge(Li) detectors. The two detectors are described by their relative full-energy efficiencies as in 7.1.2. Figure 7.3.3 shows the variation of the absolute full-energy peak efficiency E_a versus gamma-ray energy plotted for the two Ge(Li) detectors of Table 7.3.2 for the RBSS geometry.

Figure 7.3.4 shows a linear plot of the spectrum observed using the RBSS and Figure 7.3.5 shows the log plot of the spectrum of Figure 7.3.4. Most of the peaks are clearly observable and available for direct measurement. A possible source of error arises from the fact that the ^{88}Y single-escape peak is about 7 keV (at 1 325 keV) from the 1 332 keV peak of ^{60}Co. Figure 7.3.6 shows an expanded portion of the spectrum around 1332 keV for the data of Figure 7.3.4. Care should be exercised to assure that counts from the escape peak are not attributed to the peak due to the 1332 keV gamma ray.

It should also be noted that the 1173 keV and 1332 keV gamma rays of ^{60}Co are in prompt cascade and can therefore sum, resulting in errors of as much as 5%. Approximate correction factors may be determined from a knowledge of the peak-to-total ratios for the secondary gamma and the gamma-gamma angular correlation.

A similar situation exists for all radionuclides emitting gamma rays in prompt cascade.

7.3.6 *RBSS documentation*

A certificate shall be provided with each RBSS stating whether the RBSS is a certified RBSS (see 7.3.2.1) or a calibrated RBSS (7.3.2.2). In the case of the certified-solution RBSS (7.3.2.3) and the calibrated-solution RBSS (7.3.2.4), the certificate shall be for the solution alone. In any case, the certificate shall contain the following information:

1) Radionuclides used and calibrated, together with:
    a) the photon energies and radionuclide half lives;
    b) dates corresponding to the stated photon emission rates;
    c) uncertainties in the stated photon emission rates. In the case of a calibrated RBSS, the errors for the certified RBSS against which the calibrated RBSS has been calibrated and the errors in the comparison shall be given separately. In the case of a calibrated-solution RBSS, the errors for the certified solution against which the radioactive filling material solution has been calibrated and the errors in the comparison shall be given separately;
    d) density of the carrier to within 2%.
2) Calibration dates.
In the case of a calibrated RBSS, the date of calibration against the certified RBSS and the date of calibration of the certified RBSS shall be given. In the case of a calibrated-solution RBSS, the date of calibration of the radioactive filling material solution against the certified solution and the date of calibration of the certified solution shall be given.
3) Full genealogy in the case of a calibrated RBSS or a calibrated-solution RBSS including identification of the certified RBSS or certified solution against which it has been calibrated.
4) Calibrating laboratory or organization.

8. Window thickness index

Information on the thickness of the "window" (detector dead-layer, cryostat mount and endcap, etc.) can be obtained by measuring and reporting a window thickness index as the ratio of peak areas for the four energies 31 keV, 54 keV, 80 keV and 161 keV emitted by ^{133}Ba. The ratio of peak areas for the 22 keV and 88 keV energies of ^{109}Cd may also be used. Care shall be taken to ensure that self-absorption in the source and its housing are negligible.

A window thickness index based on X-ray fluorescence is used for measuring thin windows. Such an index is described in IEC 759. The thickness index is based on the X-ray fluorescence of a standard glass as described in IEC 759.

This glass contains oxides of Si, Ba, Ca, Li, Mg, Zn and B. When fluoresced with a ^{55}Fe source, it emits numerous X-ray lines in the region from 1 keV to 5 keV. Ratios of these lines to the coherently backscattered 5,9 keV line from the source are used to define a window thickness index. Refer to IEC 759 for additional details.

9. Timing

A useful measuring method for evaluating the timing capabilities of a germanium detector is based on a coincidence system detecting the two 511 keV gamma-rays of a ^{22}Na annihilation source. A "start" signal from the germanium detector under test and a delayed "stop" signal obtained from a high-speed detector are required. The distribution of the time difference between "start" and "stop", measured with a time-to-amplitude converter, gives the timing resolution of the system. Therefore, significant information on the timing resolution of the germanium detector is obtained, if the second detector and the electronics of the system are faster than the germanium detector. Such a system is described in 9.1.

9.1 *Measuring system*

Figure 9.1.1 shows a typical system for measuring the time resolution of a germanium detector. The "stop" or time reference channel consists of a fast plastic scintillator mounted on a relatively fast photomultiplier (total rise time $\leqslant$ 5 ns). The signal from the photomultiplier is processed by a constant-fraction discriminator.

The output of the discriminator is delayed before entering the "stop" side of a time-to-amplitude converter. Several calibrated delays are required for this function in order to provide a calibration of the time axis.

The germanium detector signal is split in two at the output of the preamplifier. The signal from the preamplifier is routed to a fast shaping amplifier with a differentiation time constant approximately equal to the fastest rise time observable at the preamplifier output. The differentiated signal is then routed to a constant-fraction timing discriminator. The fraction of the pulse amplitude used in this timing discriminator should be 20% and the shaping delay should be one-half of the rise time of the fastest signal observed at the output of the preamplifier. This combination of parameters helps minimize the timing uncertainties due to rise time and pulse height variations. The unshaped timing measurement signals are shown in Figure 9.1.2.

The signal from the preamplifier is also routed to an amplifier and timing single-channel analyzer which is used to gate the multichannel analyzer (Figure 9.1.1). ^{22}Na is used as a source of coincident annihilation quanta and the single channel analyzer should be centred on the 511 keV photon peak with 10% window width.

9.2 *Timing resolution*

Using a system such as shown in Figure 9.1.1, a gamma-ray coincidence spectrum is obtained. A typical spectrum is shown in Figure 9.2.1. The number of channels between the half-maximum points shall be at least 6, and the total number of counts contained within the FWHM shall be at least 4000. If computer fitting of the data is used, the 4000 minimum counts need not apply provided the FWHM is calculated by computer to within ±5% (90% confidence interval). After calibrating the time-axis with at least two calibrated delays, the FWHM and the FW 0,1 M are measured in units of nanoseconds. The following parameters shall be stated for the timing test in order to assure reproducibility:

a) germanium detector bias voltage;

b) differentiation time of the fast shaping amplifier;

c) shaping delay time.

Timing measurements are dependent on the entire electronics system and its adjustment. These adjustments are critical and difficult. Therefore the results of timing measurements should not be considered solely as characteristics of the detector.

10. Temperature cyclability

10.1 *Cyclable detectors*

Cyclable detectors are especially useful for systems which are expected to undergo warm-ups, such as portable systems, and those to be used where a continuous supply of liquid nitrogen is neither assured nor convenient.

A cyclable detector remains under vacuum as an integral part of the cryostat system. To designate a detector as cyclable, a manufacturer shall guarantee that the detector shall meet its performance specifications throughout the warranty period under conditions of unlimited cycling between room temperature and liquid nitrogen temperature and of indefinite room temperature storage.

10.2 *Annealable detectors*

Annealable detectors are cyclable detectors (see 10.1) which can be subjected to a specified temperature for a given time to reduce the effects of radiation damage. The cryostat, detector and mount shall be capable of accommodating the annealing schedule (such as 120 °C for 24 h). It should be specified that in the absence of radiation damage, the detector will be able to tolerate this annealing schedule without degrading its performance beyond specified limits.

During the annealing procedure, it may be necessary to pump the cryostat with an extremely clean vacuum pumping system.

Proper annealing can restore many radiation-damaged high-purity germanium detectors to their approximate condition prior to damage. Reverse-electrode coaxial detectors are less sensitive to small amounts of residual damage and therefore are easier to restore to their original condition than are conventional-electrode coaxial detectors.

11. Low background germanium detectors

The measurement of low-level radioactivity involves assay procedures of high sensitivity in order to differentiate the occurrence of extraneous counts having an origin other than the radioactive atoms of interest. In general, it is not possible to give simple, explicit recommendations on methods of measurement applicable for all circumstances, nor can a numerical definition of a low-background germanium detector be usefully stated for an unspecified context.

The major component of the background count of radiation detectors is comprised of responses to extraneous sources of environmental radiation such as cosmic radiation and the radioactive contamination present in the construction materials used in building the counting-room facility, shield and the detector. The other component of the background is due to the alteration of the ambient background flux by proximity to the detector of a blank sample or other extraneous materials; this may result in an increased background by scattering radiation into the detector, or a decreased background by acting as an additional shield material.

The traces of radioactive elements present in the construction material of the detector itself are related to the natural percent abundance of the radionuclides present in each material that comprises the detector assembly. Table 11.1 lists typical detector system construction materials. Radionuclides commonly present as contaminants and corresponding gamma-ray energies are listed in Table 11.2. The contribution of these contaminating radionuclides to the background of the detector is related to the specific activity of each radionuclide, the types of radioactive emissions, their energies and intensities and their proximity to the detector. However, it should be noted that the parent nuclides and their daughter products will not necessarily be in equilibrium since the processing and refinements of the constituents of raw materials are treated differently and may result in separation of the radionuclides.

Low-background germanium detectors are typically constructed from selected materials whose radionuclide concentrations are lower than those used in standard germanium detector assemblies. Materials known to be generally lower in radioactive contamination are acquired and samples are assayed for contaminating radionuclides. Only materials having suitably low levels of contamination are subsequently used to make cryostats, detector mounts and other components for low-background detectors. This presents a large materials control problem, whereby material procurement and inventories are subjected to extensive quality control on assays, machining, fabrication and subsequent isolation from other inventories.

The specific requirements for any low background detector depend upon the application. It is beyond the scope of this standard to define procedural methods or instrumentation for specific low-level assay problems or to recommend a shield and detector design that would give the lowest background and be generally applicable, taking into account the complex interrelationships among the shield composition, volume and spatiotemporal location, relative to a given detector type, volume and orientation.

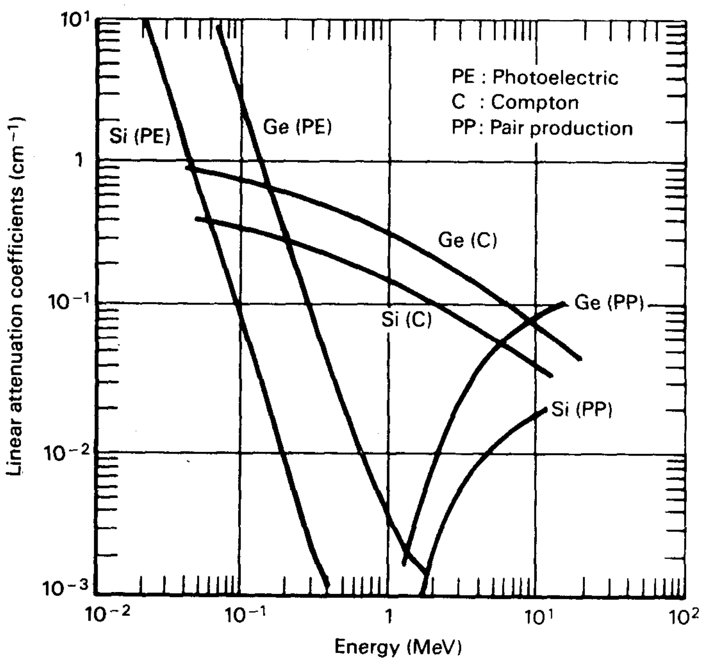

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Fig. 4.1.1 — Linear attenuation coefficients versus gamma-ray energy for Si and Ge.

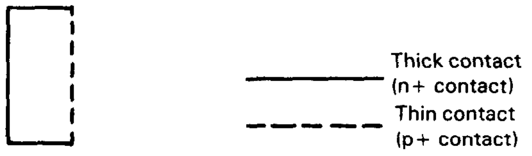

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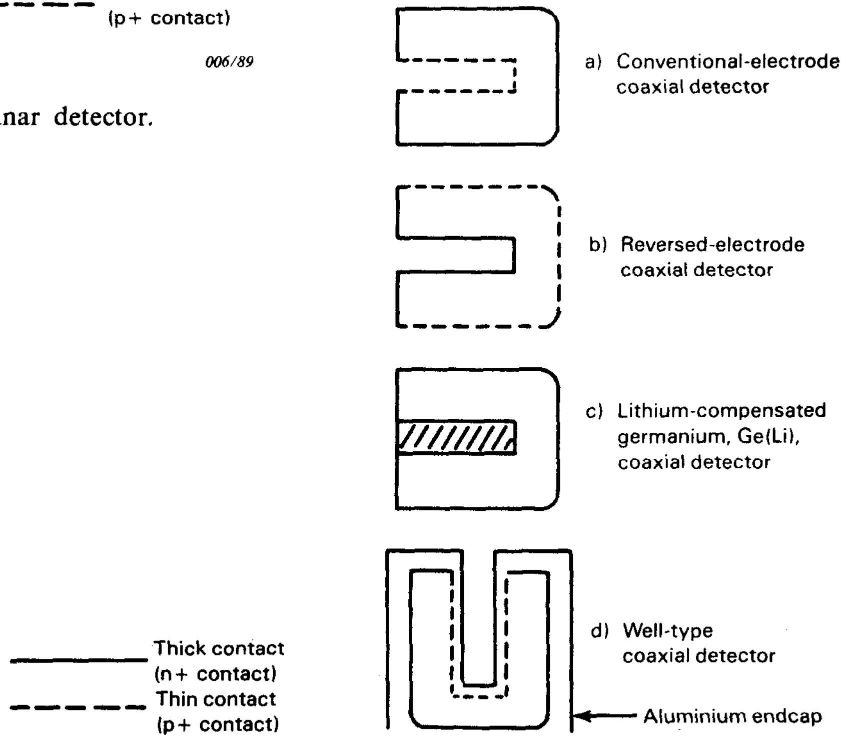
Fig. 4.3.1 — Planar detector.


a) Conventional-electrode coaxial detector
b) Reversed-electrode coaxial detector
c) Lithium-compensated germanium, Ge(Li), coaxial detector
d) Well-type coaxial detector
Aluminium endcap
Thick contact
(n+ contact)
Thin contact
(p+ contact)

007/89

Fig. 4.3.2 — Coaxial germanium detector types.

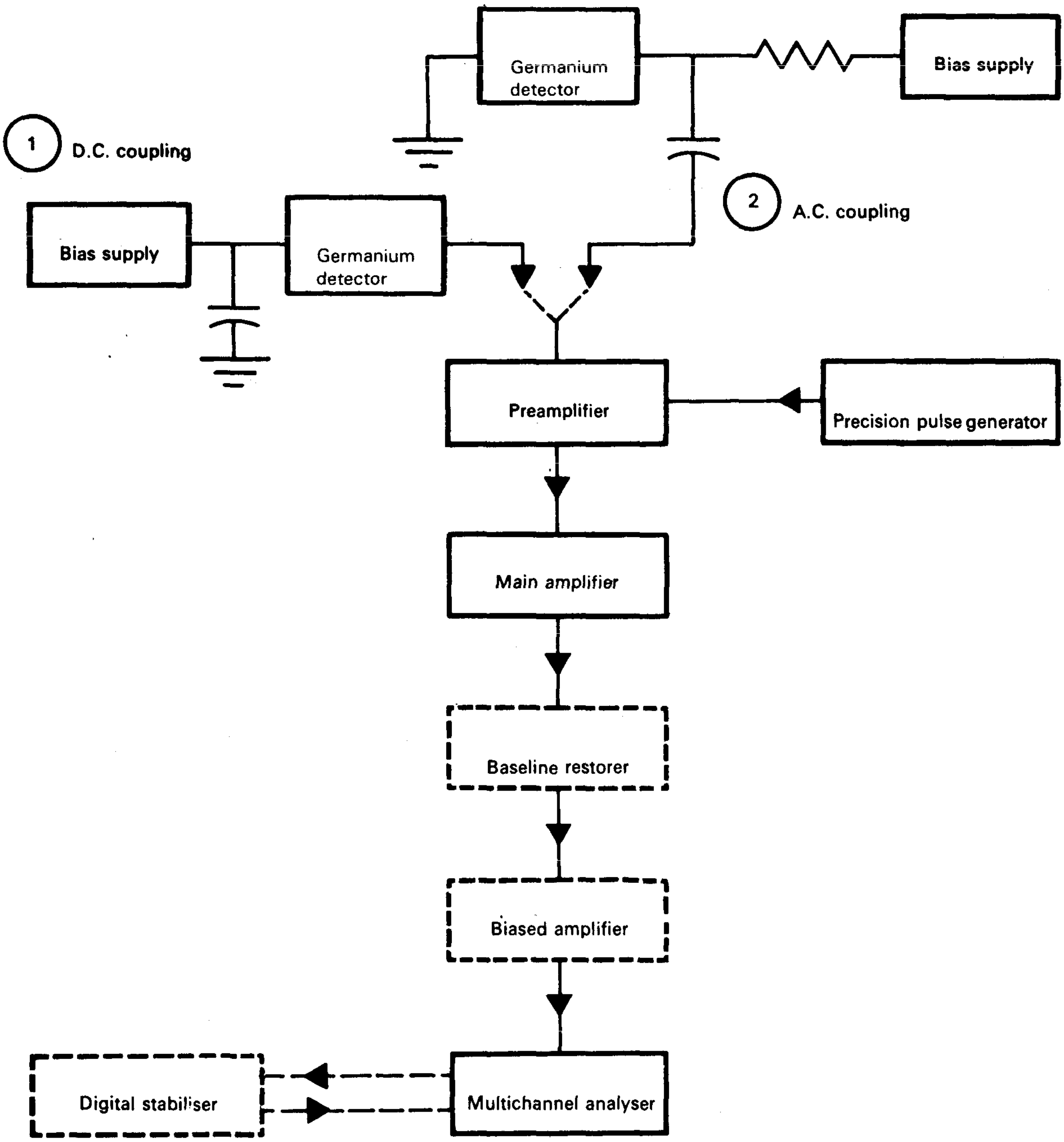


Fig. 6.2.1 — Block diagram of typical germanium gamma-ray spectrometer system. Two alternative modes of coupling the detector to the input of the preamplifier are shown.

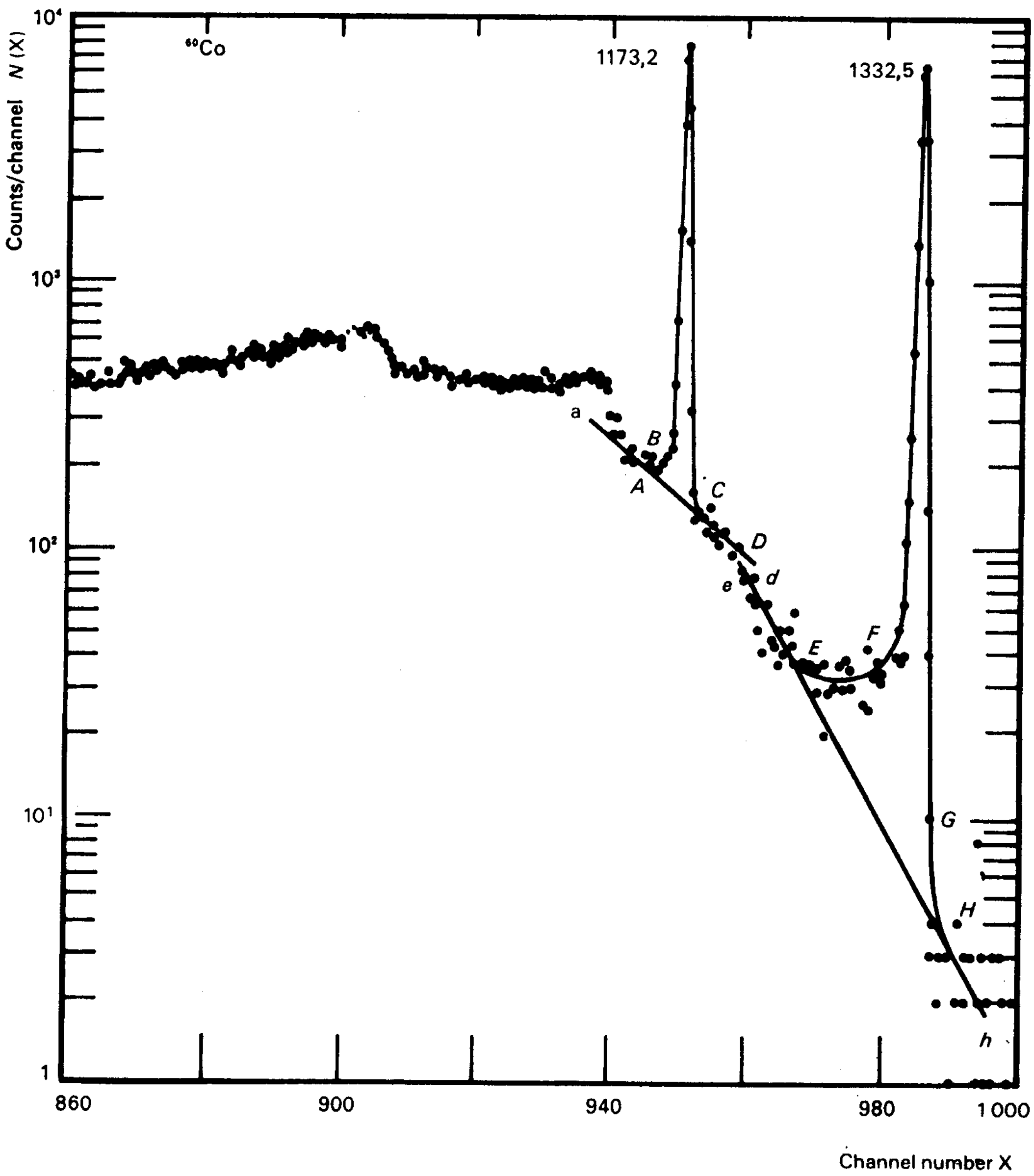


Fig. 6.3.1 — ^{60}Co gamma-ray spectrum showing straight line background approximations.

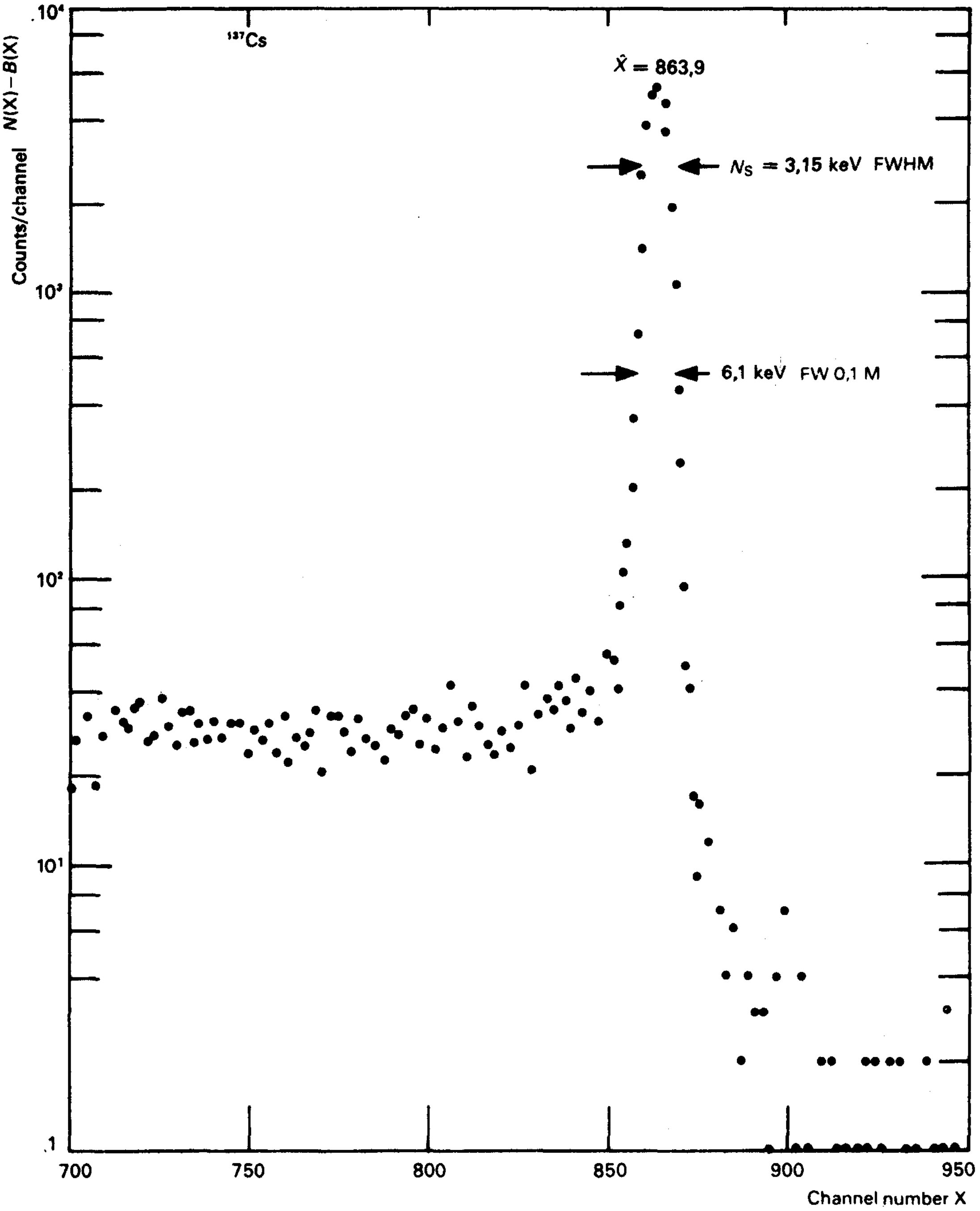


Fig. 6.4.1 — ^{137}Cs gamma-ray spectrum.

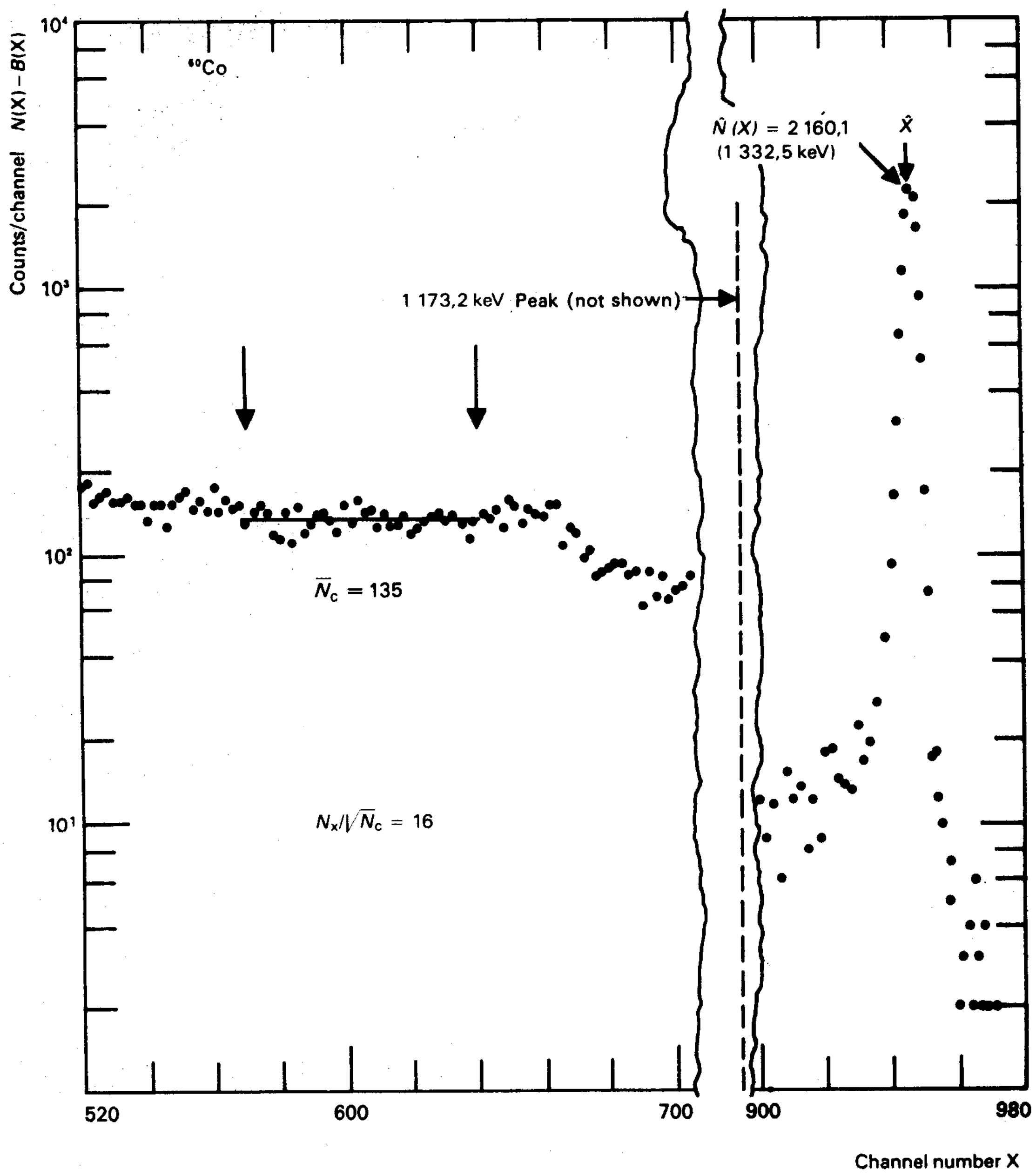


Fig. 6.6.1 — ^{60}Co gamma-ray spectrum showing determination of peak-to-Compton ratio.

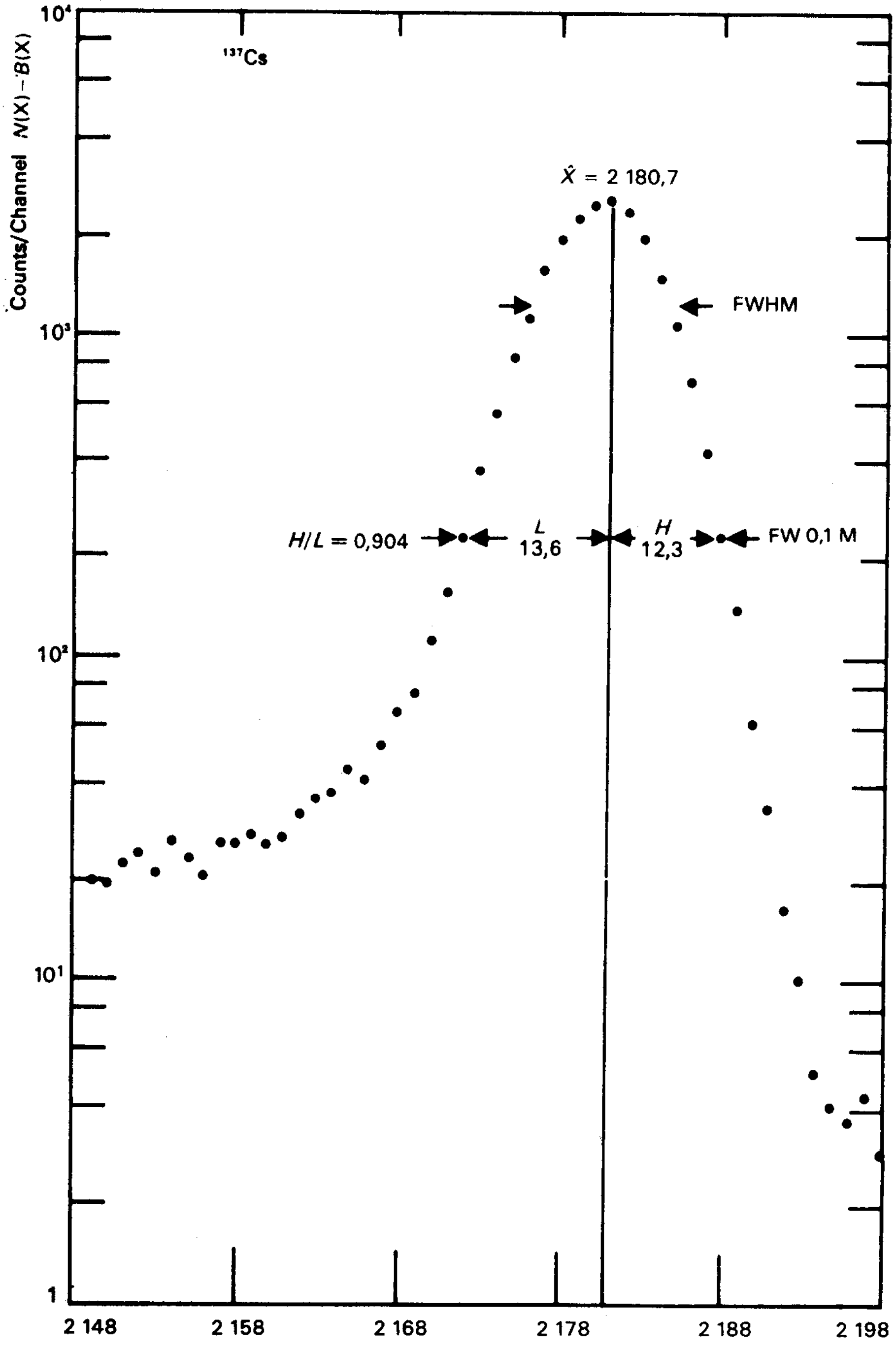
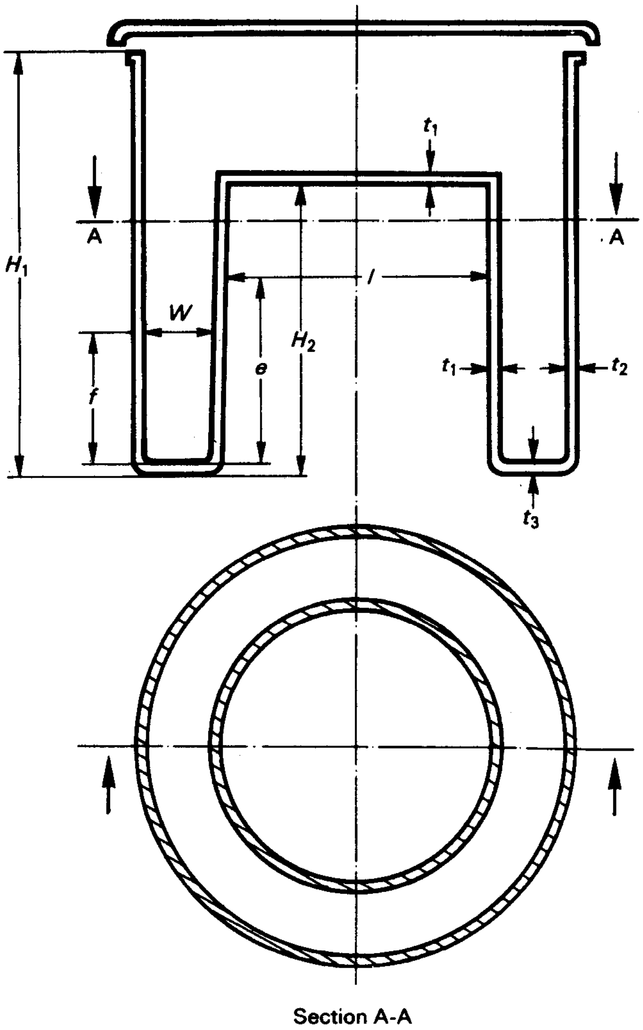


Fig. 6.9.1 — Gamma-ray full energy peak showing method of calculating peak asymmetry ratio H/L.



Model 450

	mm	inches (ref.)
H_1	104,1 ± 13	4,10 ± 0,05
H_2	6833 ± 0,15	2,690 ± 0,006
l	[77,40–0,008 *e*]	[3,048–0,008 *e*]
	± 0,10 average	± 0,004 average
	± 0,25 max.	± 0,010 max.
W	[14,83+0,008 *f*]	[0,584+0,008 *f*]
	± 0,10 average	± 0,004 average
	± 0,25 max.	± 0,010 max.
t_1	1,90 ± 0,1	0,075 ± 0,004
t_2	2,00 ± 0,25	0,079 ± 0,010
t_3	3,60 ± 0,15	0,142 ± 0,006

Model 1 000

	mm	inches
H_1	150,0 ± 1,3	5,91 ± 0,05
H_2	100,00 ± 0,15	3,937 ± 0,006
l	[120,00–0,008 *e*]	[4,724–0,008 *e*]
	± 0,1 average	± 0,004 average
	± 0,25 max.	± 0,010 max.

All other dimensions same as for Model 450

Material: plastic of density 1,1 ± 0,1

Fig. 7.3.1 — Standard re-entrant beakers.

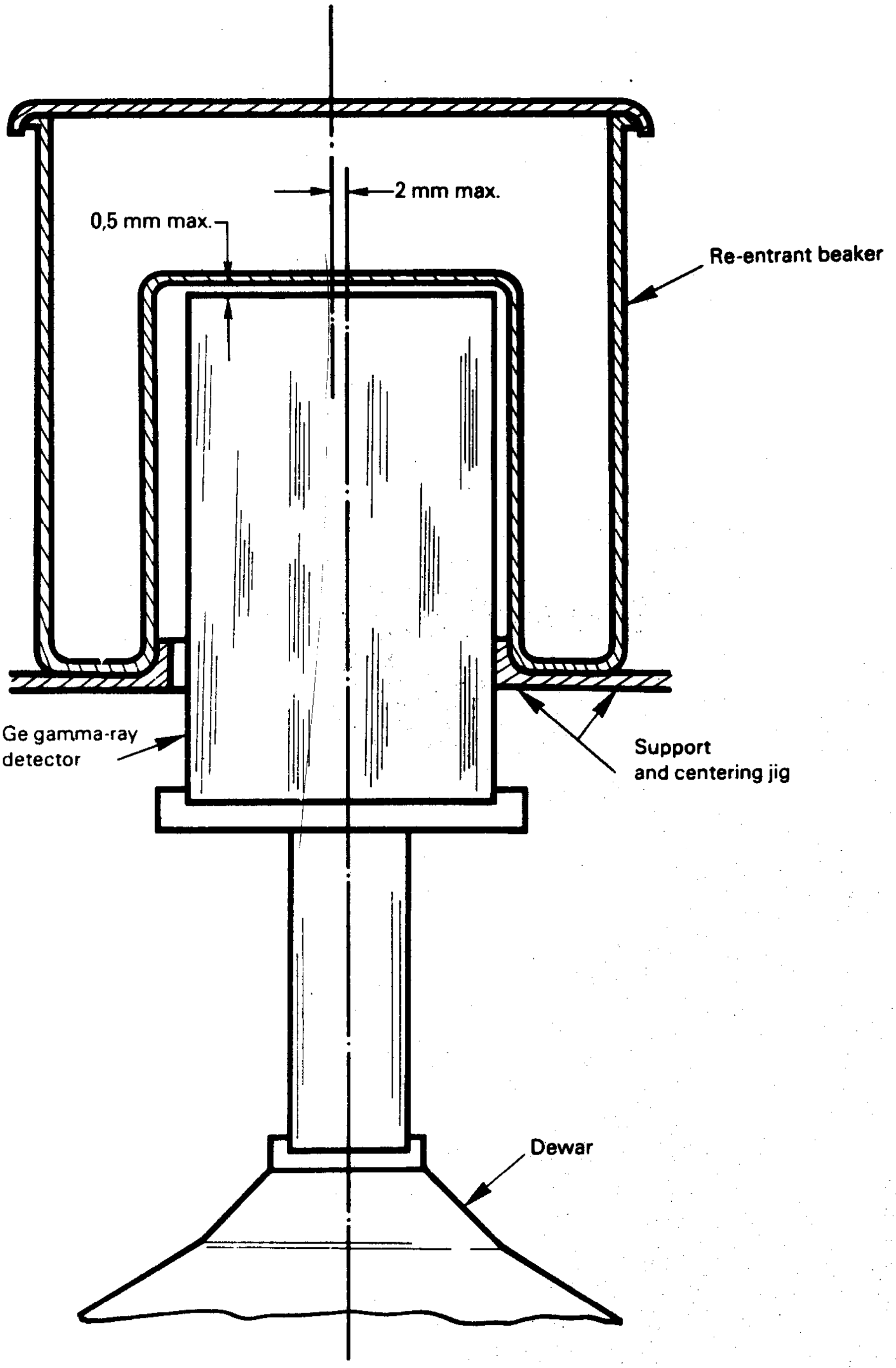
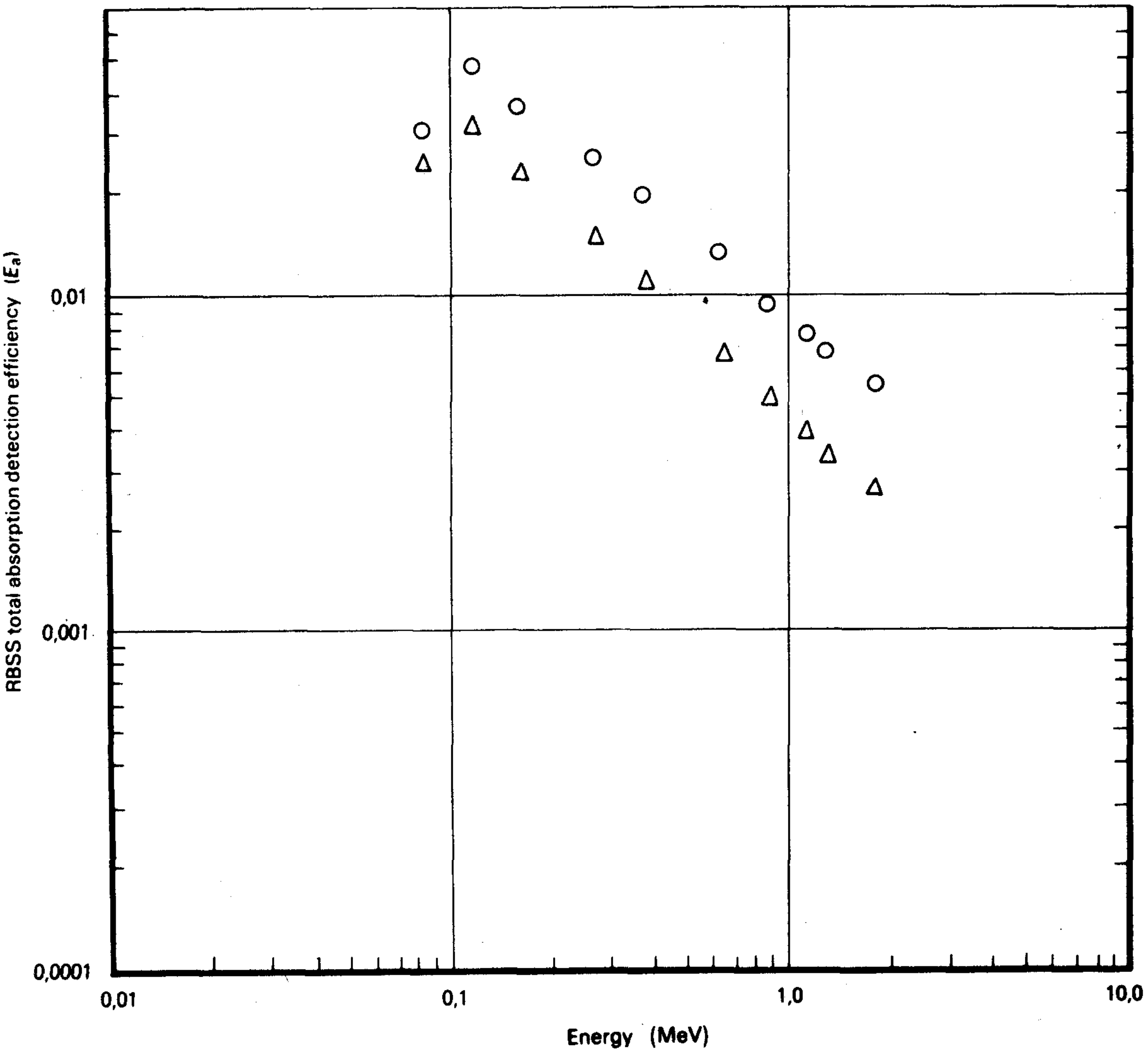


Fig. 7.3.2 — Re-entrant beaker with solid state detector.



○ = 24,5%* Ge(Li) (detector 2 of Table A2).
Δ = 11,5%* Ge(Li) (detector 1 of Table A2).
* E_{rel} (see 7.1.2.)

Fig. 7.3.3 — RBSS total absorption detection efficiency (E_a) versus energy for two Ge(Li) detectors.

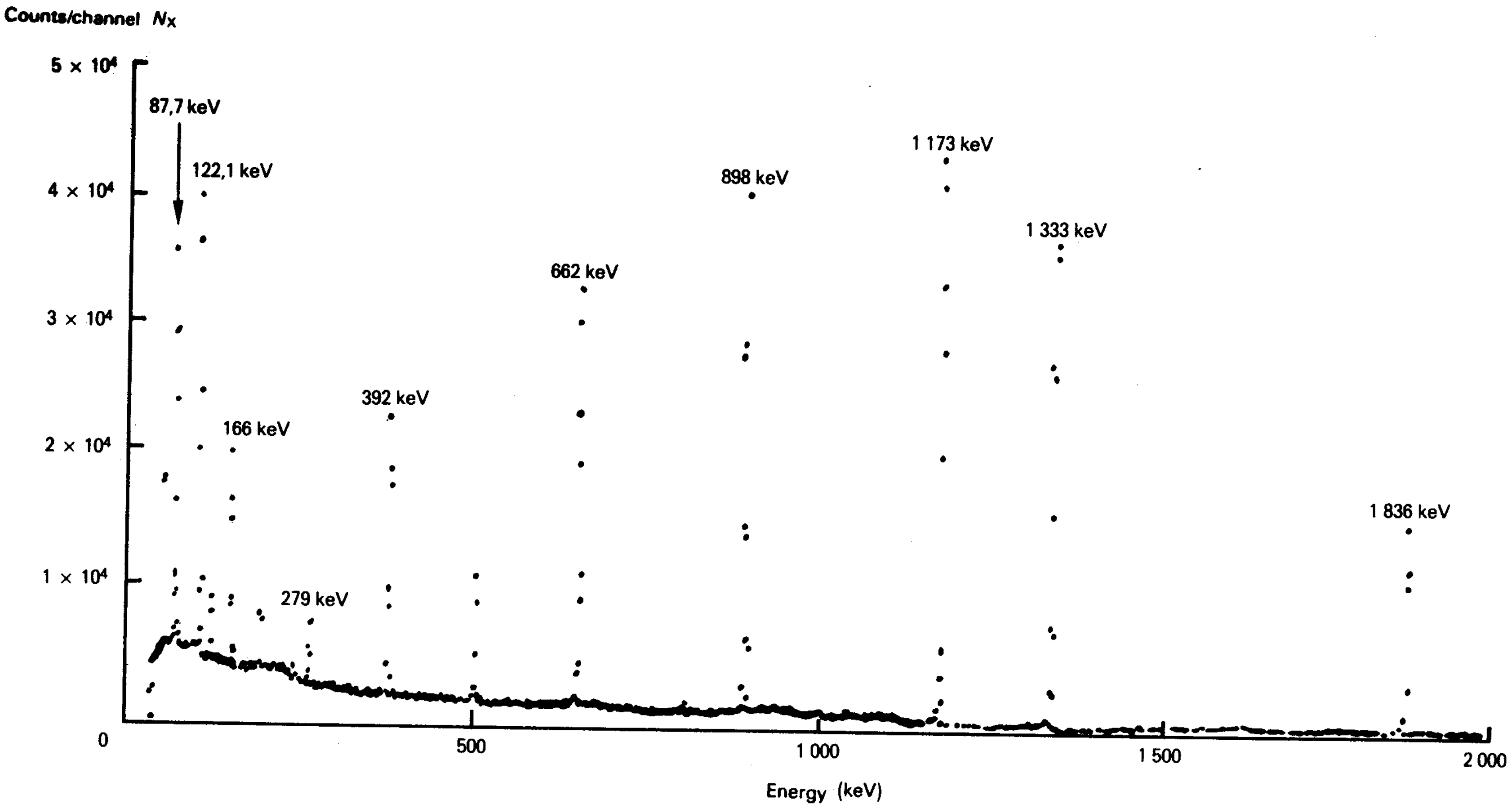


Fig. 7.3.4 — Linear plot of spectrum observed with Ge(Li) detector*, using RBSS.

*Detector 2 of Table 7.3.2.

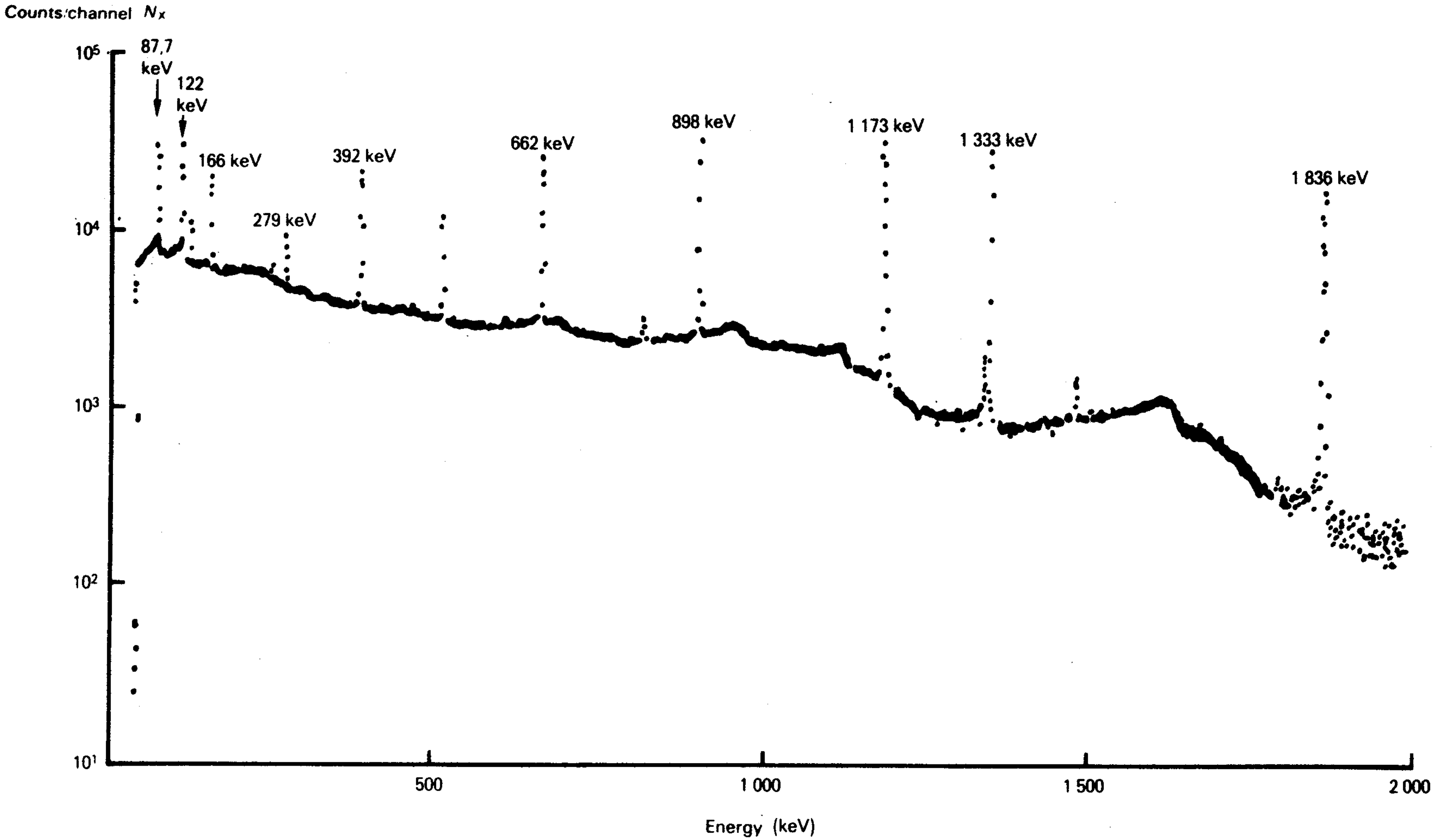


Fig. 7.3.5 — Log plot of spectrum observed with Ge(Li) detector*, using RBSS.
*Detector 2 of Table 7.3.2.

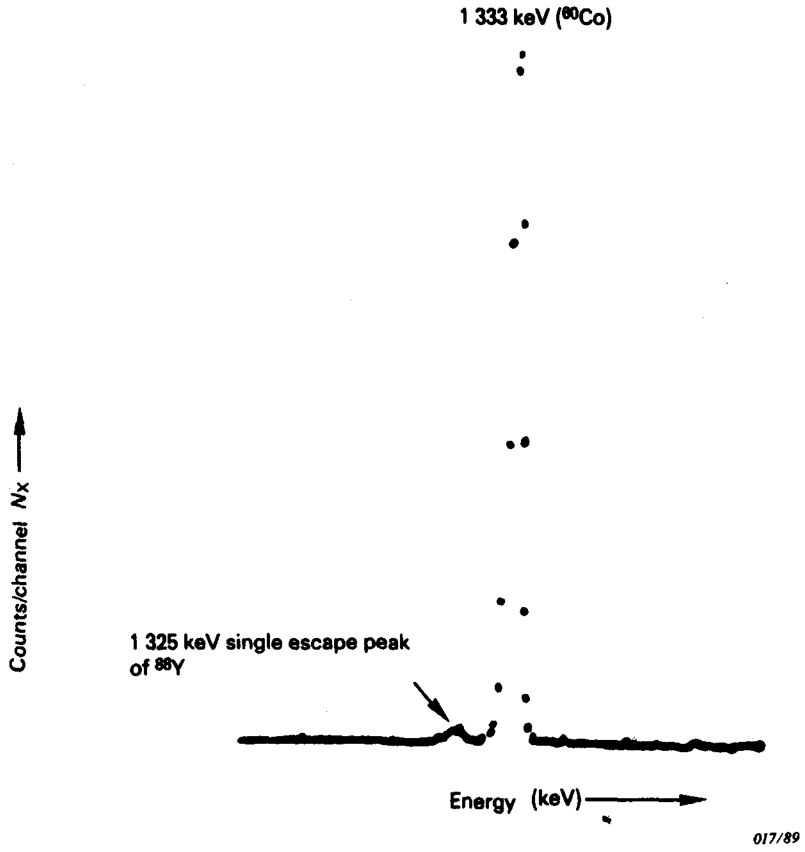


Fig. 7.3.6 — Expanded portion of Figure 7.3.4 spectrum showing 1 333 keV peak of ^{60}Co together with 1 325 keV single escape peak of ^{88}Y.

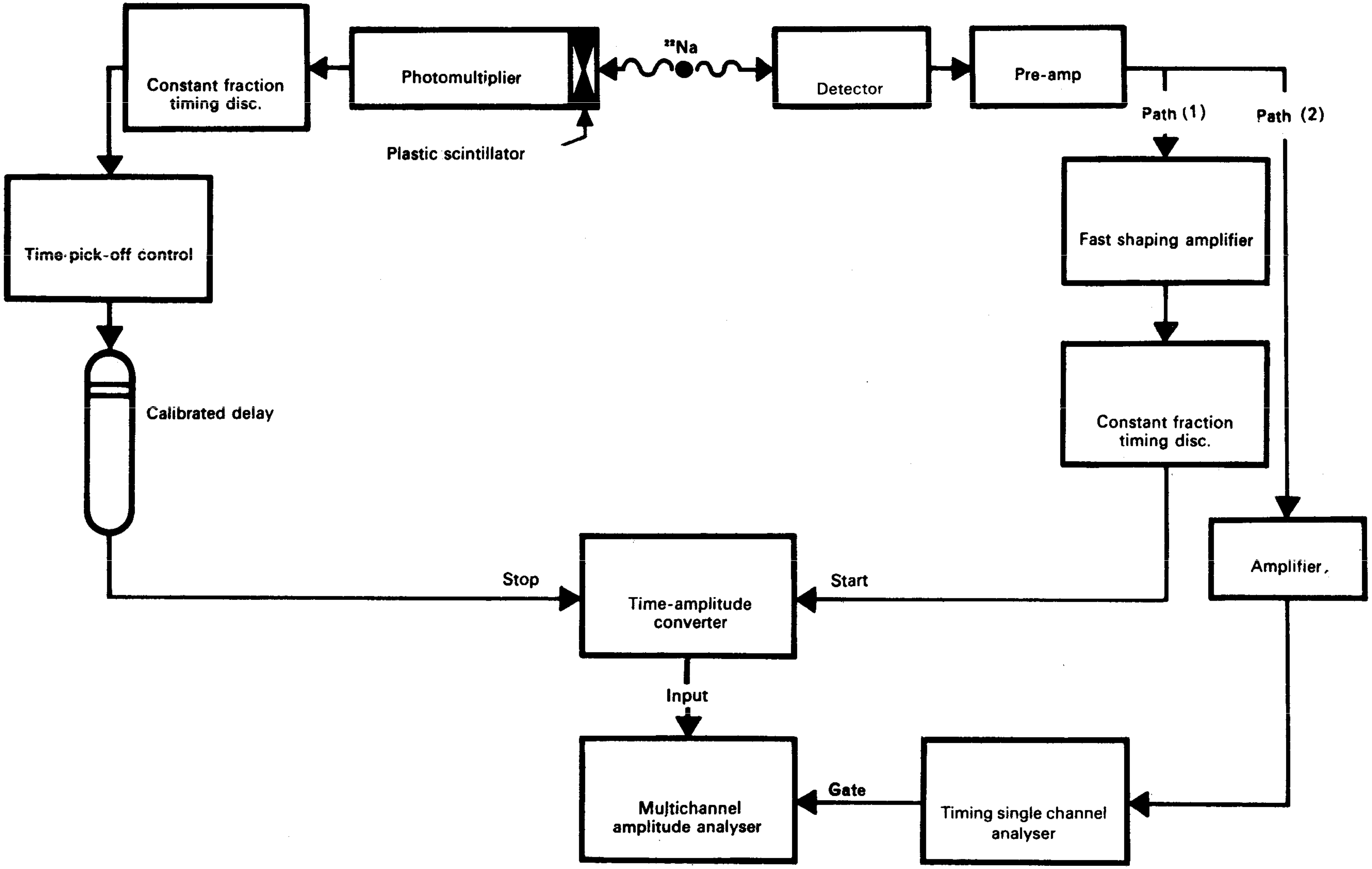


Fig. 9.1.1 — Timing measurement.

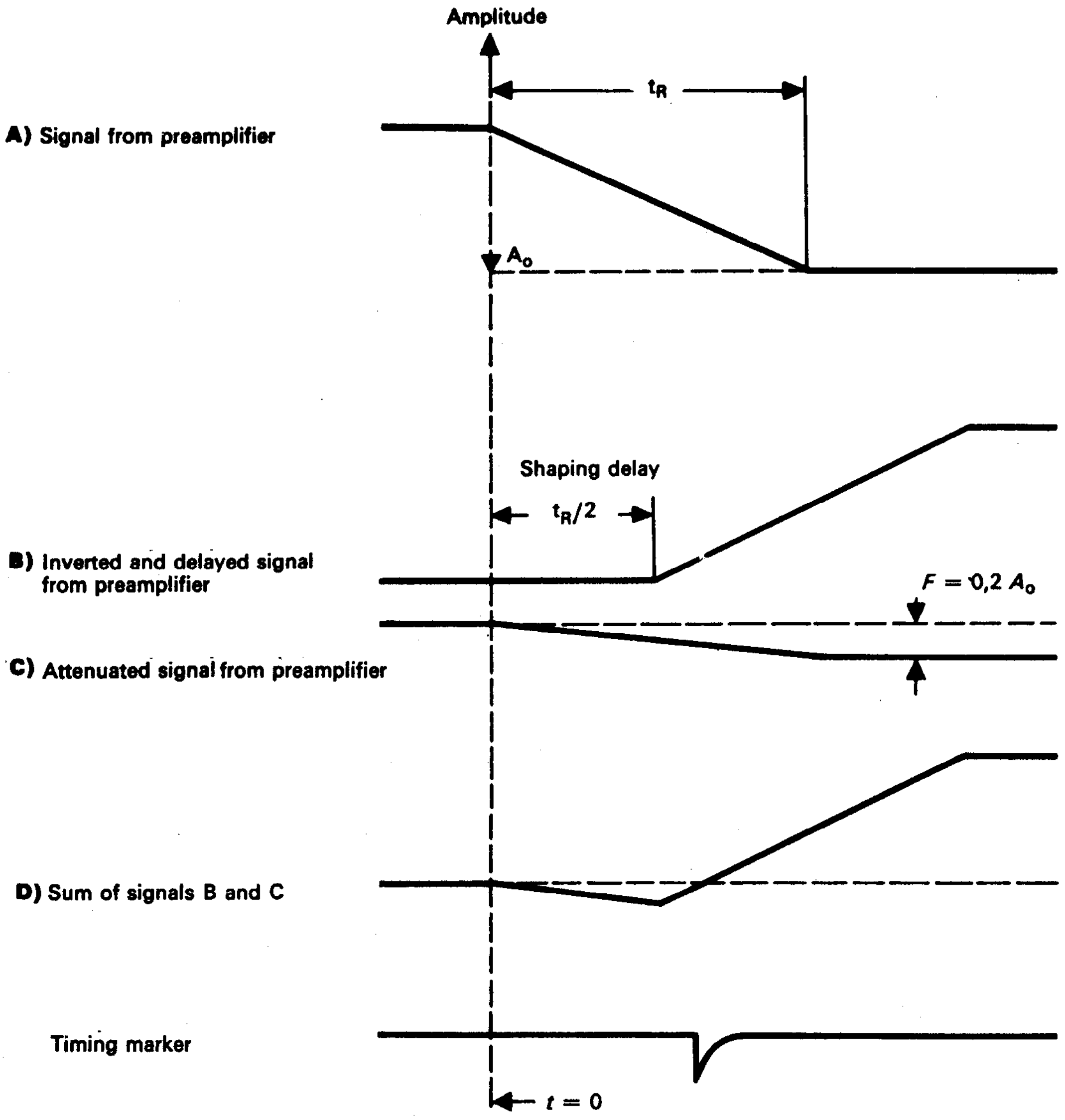

Amplitude
t_R
A) Signal from preamplifier
A_o
Shaping delay
$t_R/2$
B) Inverted and delayed signal from preamplifier
$F = 0{,}2\ A_o$
C) Attenuated signal from preamplifier
D) Sum of signals B and C
Timing marker
$t = 0$

Fig. 9.1.2 — Timing measurement signals (unshaped).

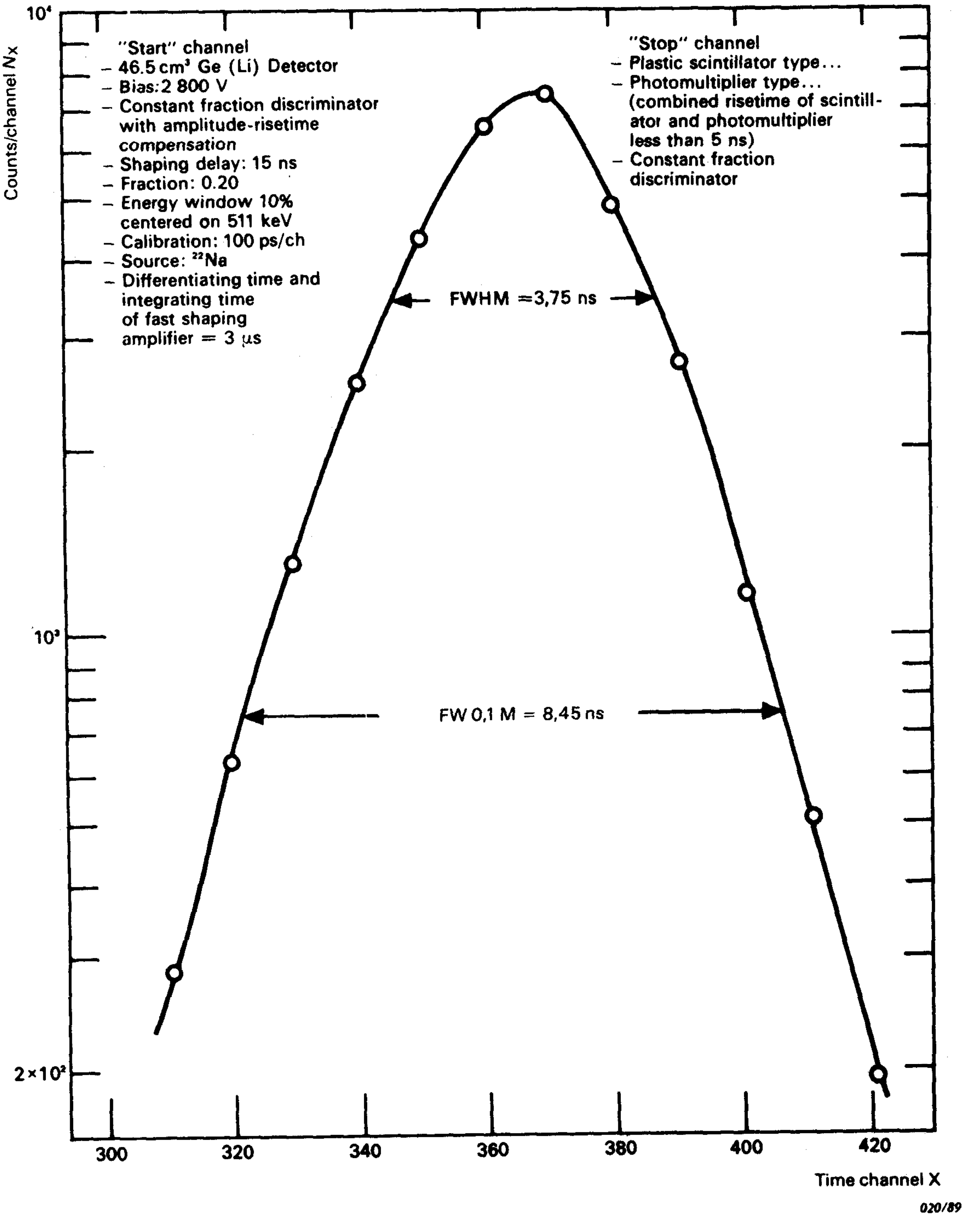


Fig. 9.2.1 — Typical gamma-ray coincidence spectrum showing fluctuations in the resolution time of a detector.

TABLE 7.3.1

Representative radionuclides for RBSS

Parent radionuclide	Energy (keV)	Half life		Typical RBSS initial emission rate in gamma s^{-1} For Model 450
^{109}Cd	88,0	464	days	200
^{57}Co	122,1	271	days	250
^{139}Ce	165,9	137,7	days	200
^{203}Hg	279,2	46,6	days	600
^{113}Sn	391,7	115,1	days	1 000
^{137}Cs	661,6	30,0	years	500
^{88}Y	898,0	106,6	days	3 500
^{60}Co	1 173.2	5,271	years	1 500
^{60}Co	1 332,5	5,271	years	1 500
^{88}Y	1 836,0	106,6	days	3 800

TABLE 7.3.2

RBSS total absorption detection efficiencies determined for two Ge(Li) detectors

Energy (keV)	E_a for detector 1 * (E_{rel} = 11,4%) **	E_a for detector 2 * (E_{rel} = 24,5%) **
88,0	0,025	0,0414
122,1	0,032	0,0484
165,9	0,0236	0,0368
279,2	0,0157	0,0260
391,7	0,0112	0,020
661,6	0,0068	0,0131
898	0,0050	0,0097
1 173	0,0039	0,0077
1 333	0,0034	0,0070
1 836	0,0026	0,0054

* Detector characteristics:

	Detector 1	*Detector 2*
Resolution at 1,33 MeV	1,88 keV	2,04 keV
E_{rel} ** at 1,33 MeV	11,4%	24,5%
Peak/Compton at 1,33 MeV	44/1	50/1
Diameter	41,2 mm	53,5 mm
Length	47,5 mm	53 mm
Diffusion depth	1,0 mm	1,5 mm
Core diameter	5,0 mm	9,0 mm
Active volume	56,2 cm^3	103,8 cm^3
Surface area exposed to beaker	74,8 cm^2	111,6 cm^2

** E_{rel} = total absorption detection efficiency relative to that of a 3×3 in (76×76 mm) NaI(Tl) scintillation crystal at a source to detector distance of 25,0 cm, where the peak area for the NaI(Tl) crystal is taken as $1{,}2 \times 10^{-3}$ N_s. N_s is the total number of 1332,5 keV gamma-ray photons emitted by the source during the life counting time (see 7.3).

TABLE 11.1

Materials commonly used in detector system construction

- Alumina
- Aluminium
- Beryllia
- Beryllium
- Charcoal
- Copper
- Gold
- Indium
- Lead
- Magnesium
- Molecular sieve
- Mylar, aluminized
- Printed circuit board
- Stainless steel
- Tin
- Tungsten

TABLE 11.2

Typical radionuclide contaminants and representative gamma-ray energies

Radionuclide	Gamma energy (keV)
$^{235}\mathrm{U}$	186
$^{212}\mathrm{Pb}$	239
$^{228}\mathrm{Ac}$	338
$^{208}\mathrm{Tl}$	583
$^{214}\mathrm{Bi}$	609
$^{137}\mathrm{Cs}$	662
$^{228}\mathrm{Ac}$	991
$^{228}\mathrm{Ac}$	968
$^{60}\mathrm{Co}$	1 173
$^{60}\mathrm{Co}$	1 332
$^{40}\mathrm{K}$	1 461
$^{214}\mathrm{Bi}$	1 765
$^{214}\mathrm{Bi}$	2 204
$^{208}\mathrm{Tl}$	2 614

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